AALTO UNIVERSITY SCHOOL OF ELECTRICAL ENGINEERING
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MARKET MECHANISMS TOWARDS SECONDARY SPECTRUM USAGE

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology.

Espoo, February 21st, 2012

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ABSTRACT OF THE MASTER´S THESIS

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Widespread adoption of smartphones, tablets and other smart devices has resulted in mobile operators (MOs) making a transition from voice to data centric business model. As a consequence there has been an increase in demand for radio spectrum. Spectrum availability in the future can be a cause of concern, the main reason of which is being attributed to the traditional and inflexible approach towards spectrum management. Hence it is required to overhaul the existing spectrum management techniques and adopt those models which aim at higher spectrum utilization.

As part of our research methodology we first perform a state-of-the-art review on secondary usage of radio spectrum. We observe that most research assumes a clean slate approach towards the emergence of secondary spectrum markets which are typically designed with an underlying assumption of participating actors being of homogeneous type. In contrast with above we take an evolutionary approach while designing market mechanisms towards heterogeneous secondary usage of spectrum. The evolution of trading markets is reflected in the incremental steps used in our research, i.e. starting from Wireless Fidelity (Wi-Fi IEEE 802.11) capacity markets, followed by super Wi-Fi (IEEE 802.11af) capacity markets and finally TV White Spaces (TVWS) spectrum leasing markets. We make use of Value Network Configuration (VNC) methodology for illustrating the design of market mechanism and further evaluate the designed mechanism using Agent Based Modeling (ABM).

Based on our simulation results we observe that a generic trade-off exist between the length of lease time, trade facilitation cost and the extent of trading activity within the markets. We also observe that there exists an optimal range of lease time for which all the market players find themselves in economically favourable situation. We compare super Wi-Fi capacity markets and TVWS spectrum leasing markets over performance of MOs and TV broadcasters and according to our evaluation local area strategy seems to offer more benefits for TVWS spectrum usage.

Keywords: Spectrum Management Models, Spectrum Database, Secondary Spectrum Trading Markets, Market Mechanism, Capacity/Spectrum leasing, Agent Based Modeling	Publishing language: English

Preface

This Master's Thesis has been written as a partial fulfillment for the Master of Science (Technology) degree at Aalto University School of Science and Technology, Finland. It was accomplished in the Department of Communications and Networking at Aalto University School of Electrical Engineering.

As I come to an end of this intellectually stimulating journey of my master's thesis, I would like to reflect back and acknowledge everyone who made it possible. First of all, I would like to thank Professor Heikki Hämmäinen for giving me this opportunity to pursue research work under his guidance. I am really grateful for his continuous supervision and encouragement during the work.

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Finally and most importantly, I want to thank my parents Sushil and Archana and my brother Atin who have kept me motivated and given me all the love and support throughout my life.

Espoo, February 21st, 2012

Ankit Taparia

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Abbreviations

3G	Third Generation
3GPP	Third Generation Partnership Project
AAA	Authentication, Authorizing and Accounting
ABM	Agent Based Modeling
ABMS	Agent Based Modeling and Simulations
AP	Access Point
CA	Consumer Agent
CAPEX	Capital Expenditure
CAS	Complex Adaptive Systems
CDBS	Commission’s Consolidated Database System
CR	Cognitive Radio
DARPA	Defense Advanced Research Project Agency
DSA	Dynamic Spectrum Access
DSL	Domain Specific Language
DSM	Dynamic Spectrum Management
DSO	Digital Switchover
DSP	Digital Signal Processing
DTV	Digital Television
EAP	Extensible Authentication Protocol
EGAN	Enhanced Generic Access Network
ETSI	European Telecommunications Standards Institute
FA	Facilitator Agent
FCC	Federal Communications Commissions
GB	Giga Byte
GBM	Geometric Brownian Motion

GPS	Global Positioning System
IDE	Integrated Development Environment
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
IPO	Initial Public Offering
ISM	Industrial, Scientific and Medical
IWLAN	Interworking Wireless Local Area Network
LAN	Local Area Network
LAO	Local Area Operator
$LAO_{Wi\text{-}Fi}$	Local Area Wi-Fi Operator
$LAO_{Wi\text{-}Fi2.0}$	Local Area Super Wi-Fi Operator
LO	Limit Order
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
mtd	mean traffic demand
Ofcom	Office of Communications
PAWS	Protocol to Access White Space
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
REPAST	Recursive Porous Agent Simulation Toolkit
RRS	Reconfigurable Radio Subsystems
SA	Supplier Agent
SDR	Software Defined Radio
SIM	Subscriber Identity Module
SpecEx	Spectrum Exchange

ST	Spectrum Trading
SU	Spectrum User
TVB	Television Broadcaster
TVWS	Television White Space
UE	User Equipment
UHF	Ultra High Frequency
UWB	Ultra Wide Band
VHF	Very High Frequency
VNC	Value Network Configuration
WA	Wide Area
WG	Working Group
Wi-Fi	Wireless Fidelity
WIG	Wireless Interworking Group
WPA	Wi-Fi Protected Access
WRAN	Wireless Rural Area Network
WSD	White Space Device
ZIP	Zero Intelligence Plus

1. Introduction

This chapter provides an introduction to our research work. Here we first discuss the motivation for our research following which the objectives, scope and research questions are described. After that we discuss the used research methodology, and finally structure of the thesis is outlined.

1.1 Motivation

Widespread adoption of smartphones, tablets and other smart devices has resulted in mobile operators (MOs) making a transition from voice to data centric business model. As a consequence there has been an increase in demand for radio spectrum and managing spectrum is becoming increasingly difficult for regulatory agencies. Recent studies conducted by Cisco (2010), Cisco (2011) show an exponentially increasing demand for mobile data and requirements for higher data rates. According to Valletti (2001) there is a general consensus within the research community that spectrum availability in the future can be a cause of concern, the main reason of which is being attributed to the traditional and inflexible approach (i.e. command and control) towards spectrum management. Under this approach regulatory bodies specify details pertaining to allowed use of spectrum, technologies which are permitted to be used, bandwidth limits, and transmitter parameters etc. According to Caicedo & Weiss (2011) command and control method of spectrum management primarily focuses on avoiding interference between users and on the type of use given to spectrum rather than on efficient use of spectrum. This argument is further supported by experimental studies conducted by Islam et al. (2008), Renk et al. (2008), McHenry (2005) identifying the presence of un-utilized and under-utilized portions of spectrum on spatial and temporal basis**.**

In order to meet the growing demands for spectrum typically two primarily solutions have been suggested – one is to improve the spectral efficiency of wireless technology and the other is to improve spectrum utilization levels by overhauling the existing spectrum management techniques. In this research work we focus on latter of the two proposed solutions considering that all the technological advances to improve spectral efficiency might not be able to keep pace with growing spectrum demand and thus in that case it is necessary to develop technical, business and regulatory frameworks for more effective spectrum management.

Some of the new models based on the principle of higher spectrum utilization are explored in Peha (1998), Peha & Panichpapiboon (2004), Faulhaber (2005), Peha (2005), Weiss & Lehr (2009). One common theme emerging from all these research work is that even though the quantity of available spectrum is fixed, the available supply could however be significantly expanded by dynamically sharing (as in Dynamic Spectrum Access (DSA)) the spectrum and hence supporting the secondary usage of spectrum. According to Olafsson et al. (2007) the core problem of spectrum inflexibility is the close coupling between the three elements of 'spectrum', 'ownership' and 'applications'. As a result one finds wireless services segregated into distinct and well defined value chain silos. According to Chapin & Lehr (2007) DSA facilitating novel business models and wireless architecture is the way forward to achieve higher levels of spectrum utilization and break these silos; in-turn altering the existing value chains and migrating towards converged future wireless services which is going to be beneficial for consumer, competition and innovation within wireless industry.

1.2 Objective, scope and research questions

The objective of our research is to design and analyze market mechanisms facilitating secondary spectrum usage across heterogeneous set of market players involving both wide area (WA) and local area (LA) operators. As a sub-objective we focus on creating a *'win-win'* scenario i.e. economically favourable conditions for sharing of spectrum among the users, across wireless network infrastructure and access right regimes. *Win-win* is considered important so that it provides incentives for the primary users to share spectrum with potential secondary users or else the potentially losing spectrum owners have many powerful means to slow down the evolution towards increasing spectrum dynamics.

Our work is an effort to extend the span of existing research work which assumes a clean slate approach and primarily concentrates on spectrum trading (ST) in between homogeneous wireless service providers as done in Caicedo & Weiss (2011), Peha & Panichpapiboon (2004).The novelty of our work lies in the fact that we are building a market involving heterogeneous players by taking incremental steps towards it. We evaluate the designed mechanism, the results of which are expected to provide inputs for deciding on technical, economic and regulatory frameworks required to institutionalize spectrum trading markets as a tool for future spectrum management.

The research on secondary usage of spectrum requires substantial knowledge of both the underlying technology models as well as the economics and business models. We do our research with an assumption that the required technology exists (i.e. technical details are beyond the scope of this research) and thus focus primarily on the economic and business models around the secondary usage of spectrum.

Having discussed the objectives and scope of our research we now state the research questions which guide the course of our research work. Following are the research questions which we primarily focus on:

- *What is state of the art literature on secondary spectrum usage?*
    - ♦ *Which of the future spectrum management models being discussed in research literature fits in our objective of designing a 'win-win' market mechanism?*
- *What are the key features to design a practical and readily implementable market mechanism facilitating secondary spectrum trading?*
    - ♦ *What incremental steps will happen in the evolution process towards the secondary spectrum trading markets?*
- *Under which conditions and assumptions is the co-existence of multiple secondary users and systems within the proposed market mechanism economically favorable for all?*
    - ♦ *What impact does introduction of trading markets have on volume of traffic flowing through network of different operators?*
    - ♦ *What impact does the length of lease time have on realizing a successful ST market scenario?*
    - ♦ *Which of the two strategies – local area or wide area, seems to offer more benefits when adopted for usage of TVWS spectrum?*

1.3 Research Methodology

For this work we use a three step approach towards research methodology. At the first step a state-of-the-art review is conducted (aided by research literature and semi-structured interview of industry experts) to illustrate important features of future spectrum management models, Wi-Fi offloading systems, Television White Spaces (TVWS) spectrum opportunities, technologies enabling future spectrum management models (specifically database system), and finally a review on various facets of spectrum trading market. This is expected to provide inputs for designing our market mechanism and evaluation procedures.

As a next step we have used an incremental approach which forms the central element contributing towards the design of market mechanism for secondary usage of radio spectrum. We have used Value Network Configuration (VNC) methodology adopted from Casey et al. (2010) for illustrating the design of market mechanism. Under VNC, participating market actors take on specific roles (aided by their technical components) and establish business interfaces amongst each other.

The designed market mechanism reflects an evolutionary approach and all the steps involved in it are such that they build upon the previous step. Finally, we considered different strategies for evaluating our design. After gauging specific requirements of our market mechanism we decided to go forward with Agent Based Modeling (ABM) (Macal & North (2010)) which is particularly suitable for modeling complex systems involving a number of interacting entities which are referred to as the agents. The fundamental feature of an agent is its capability to make independent decision based on pre-defined behavior. There are a number of open source toolkits available for the purpose of ABM and within these toolkit agents are represented as software entities.

1.4 Structure of the thesis

This thesis is structured as followed: In chapter 2 we present the state-of the-art review on all those subjects which are relevant to understand and shape the future of spectrum management. The findings of this chapter provide insights to design our market mechanism for secondary usage of spectrum. In chapter 3 we illustrate the fine details of the value network design of our market mechanism. Here we also discuss the setting up of agent based model used (i.e. model assumptions and configuration) for simulating different trading instances as part of our market mechanism. Chapter 4 is dedicated for analyzing the simulation results where we evaluate different cases across certain specified performance metrics. Finally, in chapter 5 we draw conclusions by reviewing how effectively we were able to meet the objectives of this research work, discuss our contributions and suggest directions for future work.

2. State-of-the-art review

This chapter provides the necessary background information for the research. Here we first discuss the different spectrum management frameworks existing in the research literature with an objective to identify the ones best suited for our design of win-win market mechanism. Following that we review Wi-Fi offloading systems as one possible solution for mobile operators (MOs) to ease congestion in their networks and meet the exponentially growing data demands of their subscriber. After that we explore what opportunities Television White Spaces (TVWS) band of spectrum has on offer (in terms of the amount of spectrum, deployment of different wireless technologies, potential use cases etc.) to mitigate the growing concerns of spectrum scarcity.

Next we review the technologies which are expected to be key enablers of future spectrum management techniques with a specific emphasis on database systems as it is being considered an important component within systems working on the principle of DSA. Finally, we review the literature concerning spectrum trading markets covering motivation and challenges to implement such markets, different trading mechanisms and methodology adopted for simulating and evaluating these markets.

2.1 Spectrum management tools

Traditionally command and control approach has been used for managing the spectrum which is based on static spectrum allocation model Olafsson et al. (2007). Considering the legacy mobile networks, such an approach has been vital for large scale diffusion, harmonization and standardization process for various radio access technologies, for e.g. – GSM. However Tonmukayakul & Weiss (2004) says that it is important to understand that radio spectrum is a multi dimensional (space, time and frequency) entity where command and control approach leads to a barrier in accessing these various dimensions. Legacy spectrum management tools do not factor in the importance of spectrum utilization and with rising concerns about spectrum crunch, they are going to hamper the development of new and innovative wireless services. Hence there is a requirement for alternative spectrum management models which would allow a more efficient and flexible utilization of spectrum in future. Dynamic Spectrum Management (DSM) can break the above mentioned barriers in one or more of the dimensions.

With a possibility of spectrum crunch in future, a considerable amount of research has been done to identify alternative spectrum management models which would allow a more efficient and flexible utilization of spectrum. These research works discuss various facets of spectrum management on technical, economical and regulatory fronts. Here we try to classify these numerous studies so as to reveal the state-of-the-art of future spectrum management models. This will provide a better understanding of the tools required to manage spectrum efficiently, give an overview of the solutions proposed in the current literature, and more importantly will help in identifying the gaps to be filled in future studies. It also does provide inputs for designing our win-win spectrum management framework.

Nekovee (2006) has identified three distinct models for spectrum management:

- The license-exempt model (open spectrum)
- Secondary usage of the licensed spectrum
- The market model

According to Chapin & Lehr (2007) it is important to identify those spectrum management models which are going to fuel-in the initial commercialization of CR and DSA technologies. A *'win-win'* business model where all the participating market players have incentives to contribute and promote realization of such technologies could be one possible way of moving ahead. Table 2-1 categorizes different spectrum management models proposed in research literature having similar characteristics under three models as proposed by Nekovee (2006) and identifies those which fall in *'win-win'* category. This would help in better understanding of numerous complementary spectrum management models currently existing in literature. In the following sub-section we discuss each of these models in detail.

Table 2-1 Categorization of different spectrum management models

Spectrum Model	Complementary Models	Comments
License-exempt (open spectrum)	- Public commons (Niyato & Hossain (2008)) - Open Approach (Hwang & Yoon (2009)) - Spectrum Commons Coexistence Cooperation (Peha (2007))	- Does not represent a win-win scenario
Secondary usage of licensed spectrum	- Private commons (Niyato & Hossain (2008)) - Commons Approach (spectrum sharing) (Hwang & Yoon (2009)) - Primary-secondary sharing with coexistence (Peha (2007))	- Transmission according to underlay or overlay approach (Niyato & Hossain (2008)) - win-win if revenue sharing mechanism otherwise not
Market Model	- Property rights approach (Peha (2007)) - Exclusive usage model (Niyato & Hossain (2008)) - Primary-secondary sharing based on cooperation (Peha (2007))	- real time or non real time ST markets (Attar et al. (2008)) - a win-win scenario

2.1.1 The license-exempt model (open spectrum model)

The first proposed approach of managing spectrum in future is to adopt a model which Nekovee (2006) refer to as the license-exempt (open spectrum). License exempt usage could be of two types – dedicated unlicensed (explained in this sub-section) and the other which is a relatively newer concept involving unlicensed on secondary usage basis (discussed in next sub-section).

This model has also been referred to as the as ‘Public commons model’ in Niyato & Hossain (2008) , ‘Open Approach’ in Hwang & Yoon (2009) and ‘Spectrum Commons based on coexistence’ in Peha (2007). According to these models the radio spectrum must be made open to anyone for access with equal rights under a minimum set of restrictions called spectrum etiquette as defined by standardization bodies, regulators or industry players. Researchers advocating this approach argue that unlicensed use of spectrum would play a crucial role in supporting innovation process and in maximizing the benefits from advancements in mobile communication.

This spectrum management framework has been successfully applied to 2.4-2.483GHz, 5.725-5.78GHz ISM (Industrial, Scientific and Medical) band where the wireless standards such as IEEE 802.11 (Wi-Fi), cordless phones and Bluetooth co-exist. The Wi-Fi standards have been widely adopted, as best demonstrated by the rise of WLANs (Wireless Local Area Network) and have spurred tremendous innovation and productivity. Despite the considerable interference in these bands, WLAN presents the most popular and successful wireless access to internet today. Large scale roll-outs of wireless APs (Access Point) based on IEEE 802.11 protocols are planned and have in some cases already been undertaken. The success of WLANs, in spite of intensively used spectrum and considerable interference, provides strong support for the case of making unregulated spectrum available for wireless access (Olafsson et al. (2007)). All above mentioned variants find a close synergy between them; however Peha (2007) further classifies the Spectrum commons model based upon the cooperation strategies. In this commons model all devices cooperate and there is a requirement that all devices must share a detailed communications protocol.

2.1.2 Secondary usage of the licensed spectrum

As an alternative for future spectrum management, Private commons model (Niyato & Hossain (2008)) is very popular. This particular spectrum management framework has been referred to as Commons Approach (spectrum sharing) in Hwang & Yoon (2009) and Primary - Secondary sharing with coexistence strategy in Peha (2007). This model is based upon secondary usage of the licensed spectrum and its key enablers include innovative sensing technologies, cognitive radio (CR) networks, global positioning systems (GPS) and Software defined radio (SDR).We discuss in detail about these enabling technologies in following sections.

One of the operators has primary usage rights (the one who has been assigned an exclusive license for a spectrum band) which guarantees the required quality of service (QoS) for its subscribers, and there exist one or more secondary systems operating together. In principle secondary users should operate without causing any harmful interference to the primary. The secondary users facilitated by technologies mentioned above identify sections of idle spectrum in the licensed frequency bands and then transmit over these bands by either adopting an underlay or an overlay approach.

In the underlay approach a secondary user spreads the transmission over a large bandwidth using low transmission power (e.g., ultra-wideband [UWB] transmission).The idea here is that secondary devices transmit at such low power that they never cause interference and essentially are invisible to the primary system.

In the overlay approach a secondary user access the spectrum in the frequency or time domain and transmit opportunistically only after sensing the environment and ensuring that transmissions do not cause harmful interference. Here secondary user's access rights are overlaid on top of the primary user so as to exploit opportunities when the primary user is not actually utilizing the spectrum. While power control is crucial for underlay access, spectrum opportunity identification and synchronization are important for overlay access (Niyato & Hossain (2008)).

The model further split into two branches depending upon the nature of secondary users – unlicensed or licensed. In case of unlicensed secondary users the QoS need not be guaranteed as there can be many other unlicensed secondary users transmitting in the same spectrum region, which is difficult to sense and manage. One of the examples falling in this category is that of unlicensed reuse of TV broadcast channels (TV white spaces) by CRs. A number of standardization activities are being carried out by IEEE (Institute for Electrical and Electronics Engineers) working groups in order to exploit the TVWS potential and ensure a commercially viable use case. Some of these activities include IEEE 802.11af Super Wi-Fi, IEEE 802.22 Wireless Rural Area Network (WRAN) and IEEE 802.19.1 coexistence of TVWS devices. We discuss about these standardization activities in detail within TVWS section.

In the case of licensed secondary spectrum users there is a possibility of assuring QoS as the secondary system need not be concerned about interference from other secondary users. They still need to follow certain spectrum etiquette so as to avoid causing harmful interference to primary users. Mobile operators can be given an exclusive access to transmit opportunistically in TV white spaces or guard bands thus presenting an example of licensed secondary users operating with a primary system in a non-coordinated opportunistic manner. As shown above, a number of primary-secondary arrangements are possible which are going to become more practical with regulatory reforms supported by technological advancements.

2.1.3 The market model

Finally we explore the market based model which has been referred to as the Property-rights approach in Hwang & Yoon (2009)**,** Exclusive usage model in Niyato & Hossain (2008) and Primary-secondary sharing based on co-operation in Peha (2007). Attar et al. (2008) further classifies such kind of markets being real-time and non real-time ST markets. As within the current spectrum assignment process, in order to protect spectrum users against the interference, licenses are granted with exclusive rights. However within this new model, licensee gets a right to further sell or lease its spectrum usage rights to other market players. As a result of which the spectrum could be reallocated from low-value users to high-value users. Spectrum trading interaction ensures that this model is going to be based upon cooperation where selling or leasing of spectrum usage rights is analogous to that of secondary user taking permission before transmitting from primary user.

Such kind of mechanism would ensure that primary users make profits out of their otherwise un-utilized or underutilized portions of spectrum while secondary users could have an access to new spectrum with a guaranteed QoS. Other potential gains includes more efficient companies displacing inefficient ones and expanding; and new companies getting an access to spectrum to enter new and existing markets (Chapin & Lehr (2007)), thereby increasing competition and technological developments. However for such ST markets to succeed we need to analyze and decide on various matters such as nature of market settings and players (homogeneous or heterogeneous), optimum lease times, defining tradable usage rights and overcoming other potential inefficiencies and challenges. We discuss more details on ST markets later in a section primarily focusing on it.

2.1.4 Dynamic spectrum access: taxonomy

IEEE P1900.1 working group (IEEE P1900 WG (2006)) has defined Dynamic Spectrum Access (DSA) as “technique by which a radio (system) dynamically adapts to select operating spectrum to use available (in local time-frequency space) spectrum holes with limited spectrum rights”. According to Nekovee (2006) DSA is one of the more developed forms of CR technology. DSA also take place in several forms and has its two main branches as cooperative and non-cooperative. The form of DSA network architecture required varies accordingly. Nekovee (2006) discuss different architectures associated with DSA and classifies them broadly under centralized, decentralized, and fully autonomous categories. Niyato & Hossain (2008) further argues that the used DSA protocol depend on the nature of interaction (i.e. either cooperative or non-cooperative) between the CR entities. Next we discuss the requirements of different architecture of DSA in more detail.

I. **Centralized approach to cooperative DSA** – This approach requires a centralized control entity to gather all the information on spectrum availability from primary users (supply side) and spectrum requirements from secondary users (demand side). The centralized entity further matches the demand and supply side. Spectrum is assigned in an optimal manner such that it maximizes the revenue of a primary service provider and/or utility of secondary users. Such kind of DSA architecture would be required in spectrum trading markets where the role of centralized control entity would be taken by the spectrum exchange facilitated by brokers and auctioneers.

II. **Centralized approach to non-cooperative DSA -** In such a system there exist a centralized CR controller and a number of CR devices with spectrum sensing capabilities. The CR devices continuously perform spectral measurements and report it back to the CR controller signaling the presence, if any, of primary users. The centralized controller thus has complete network information. It uses the reported signals from CR devices and also its own measurements to achieve a reliable detection and prediction of idle spectrum. An example of such architecture has been described in Weiss & Jondral (2004).

III. **Decentralized & autonomous approach to non-cooperative DSA** –This architecture is based on the sensing techniques of the CR entities which have their independent objectives and do not collaborate with each other which may result into a hidden node problem. A CR device senses the spectrum it wishes to use and determine the presence of primary users and other CR devices. Based on the sensing information, the device identifies spectrum opportunities (frequency, time, space, and code), and transmits in a manner such that it does not cause interference to the primary users and limit it to other CR devices through defined spectrum etiquettes. Most notable example of this approach is the DARPA (Defense Advanced Research Project Agency) next generation program in the USA (Horne (2003)).

IV. **Decentralized approach to cooperative DSA** – In this architecture there is no centralized controller and instead all the CR entities form a localized group to pool in their sensing information. These groups of CR collaborate with each other, both in identification of spectrum opportunities and in utilization of these spectrum resources. There is a drawback associated with this approach concerning the communication overhead which is caused by frequent exchange of coordination and control messages between the CR devices.

2.2 Mobile data offloading to WLAN systems

Rapid consumer uptake of smartphones, cellular-enabled tablets and netbooks has resulted in an upsurge of mobile data usage. The result of which is that the mobile operators are facing a challenge to explore other avenues of meeting this increase in demand for data which is overtaking most of their cellular network capacity. Wi-Fi offloading can be one possible solution to these challenges. According to Balasubramanian et al. (2010), Doufexi et al. (2003) with high capacity and low implementation cost Wi-Fi is an ideal technology for expanding cellular data capability.

There is a ubiquitous excess Wi-Fi capacity available in dense urban areas which could be used by mobile operators to relax the data congestion in their own networks. Thus the strength of Wi-Fi solutions will be in the existing capacity on offer through WLAN systems deployed in public places, community networks and individual households. The challenging task from an operator point of view is to get an access to this fragmented Wi-Fi capacity in a managed and secured way which requires an interworking and integration solution in between 3GPP (3rd Generation Partnership Project) technologies and WLAN systems. Several WLAN standardization organizations (in particular ETSI, IEEE 802.11, IEEE 802.15) have agreed to set up a joint wireless interworking group (WIG) to deal with the interworking between WLANs and cellular networks. This section discusses about the initiatives taken by 3GPP to develop a cellular-WLAN interworking architecture as an add-on to the 3GPP cellular system specification. Later in this section we also discuss some of the existing business models and solutions centered on Wi-Fi offloading.

2.2.1 Interworking architecture between 3GPP and WLAN systems

WLANs can cover only a small area and allow limited mobility, but provide higher data rates. Therefore, WLANs are well suited to hotspot coverage where there is a high density of demand for high data-rate wireless services requiring limited mobility. On the other hand, 3G wireless networks, with their well-established wide coverage, and high mobility, are more suited to areas with moderate or low-density demand for wireless usage requiring high mobility. Therefore, WLANs and 3G can be seen as complementary.

The integration of 3G wireless and WLANs is highly significant to make wireless multimedia and other high data-rate services possible for a large population. A multimedia 3G/WLAN terminal can access high-bandwidth data services where WLAN coverage is offered, while accessing wide area networks using 3G at other places.

According to Garg (2007) the primary interworking objectives and requirements are as followed:

- Common billing and customer care. This is the simplest form of interworking that provides a common bill and customer care to the subscriber but otherwise requires no real interworking between the WLAN and 3GPP data networks.
- 3GPP-based access control and charging. This requires authentication, authorization, and accounting (AAA)[1] for subscribers in the WLAN to be based on the same AAA procedures used in the 3GPP data networks. It means a mobile subscriber can use his or her subscriber identity module (SIM) to access WLAN services.
- Access to 3GPP-based packet switched services. The aim of this requirement is to allow the mobile operator to allow access to its 3GPP data services to subscribers in a WLAN environment. It means a mobile subscriber should be able to access/select 3GPP data services through the WLAN access network.
- Service continuity. The goal is to allow seamless service continuity across the 3GPP and WLAN systems. It means that a user session during mobility across these networks should not only continue but also should not have noticeable service change in terms of quality and disruption.
- Access to 3GPP circuit-switched services. The goal of this requirement is to allow the 3GPP operator to offer access to circuit-switched services such as voice calls from the WLAN systems.

ETSI (European Telecommunications Standards Institute) has specified two generic approaches for interworking – tight coupling and loose coupling. With tight coupling

[1] Cisco has developed an innovative next-generation hotspot strategy based on IEEE 802.11u, Wi-Fi Protected Access 2 (WPA2)-Enterprise and standards-based Extensible Authentication Protocol (EAP) methods which enable MOs to offload data traffic securely to Wi-Fi (Cisco (2011))

the WLAN is connected to the 3GPP core network in the same way as any other radio access network. In this case, the WLAN data traffic goes through the 3GPP core network before reaching the external packet data networks. Thus in this architecture Wi-Fi provides an alternate radio access for standard 3G RAN. In 3GPP release this kind of architecture is called as Enhanced Generic Access Network (EGAN) architecture. The following figure taken from Gunasekaran & Harmantzis (2008) illustrates the tight coupling interworking architecture.

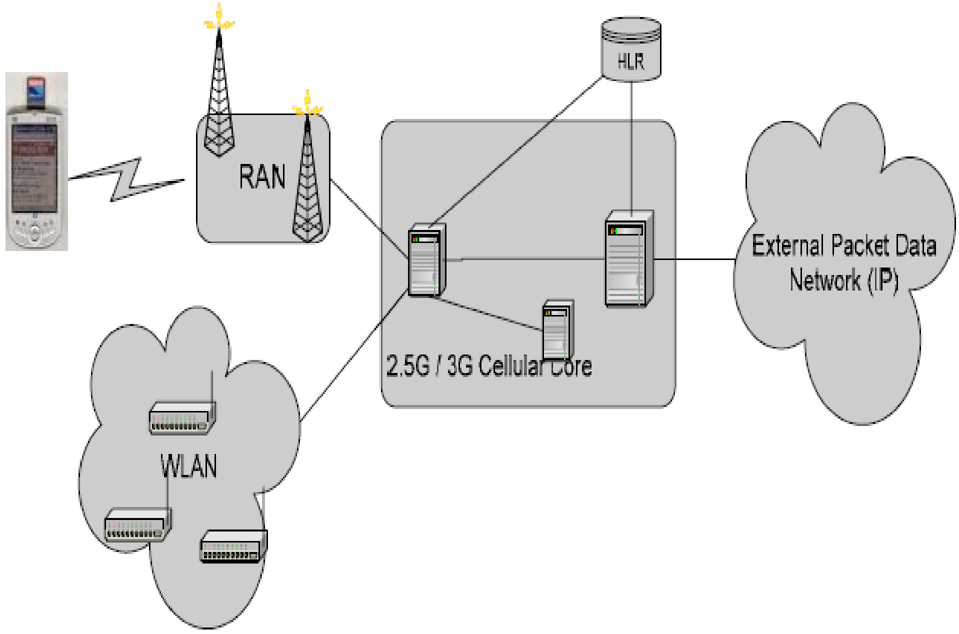

Figure 2-1 Tight coupling interworking architecture between 3GPP and WLAN as described in Gunasekaran & Harmantzis (2008)

In case of loosely coupled architecture the WLAN is integrated with the 3GPP network in the operators IP network, thus in contrast to tight coupling, the WLAN data traffic does not pass through the 3GPP core network but goes directly to the operator's IP network. This approach is called Interworking Wireless LAN (IWLAN) architecture. The following figure illustrates the loose coupling interworking architecture.

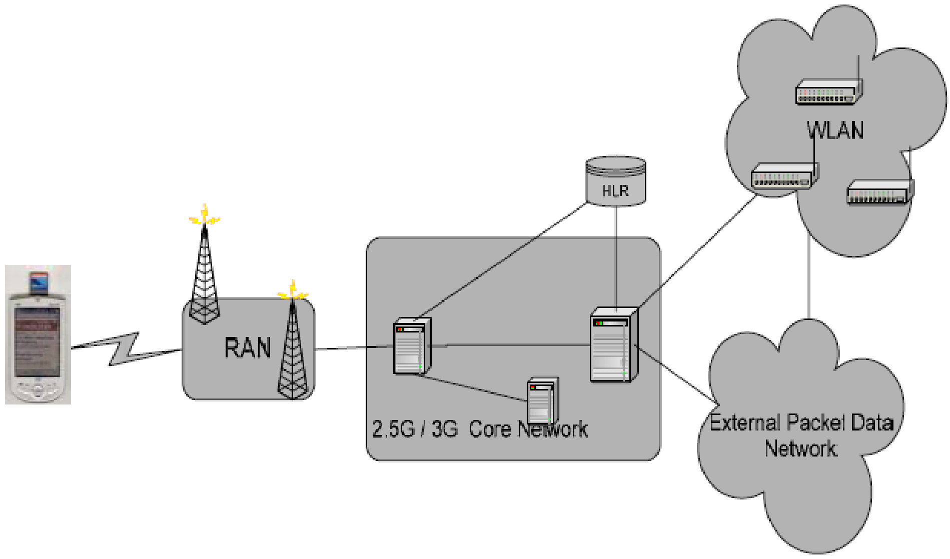

Figure 2-2 Loose coupling interworking architecture between 3GPP and WLAN as described in Gunasekaran & Harmantzis (2008)

2.2.2 Existing models centered around Wi-Fi offloading

In this sub-section we discuss some of the existing Wi-Fi offloading business models and solutions which have been developed for MOs to take advantage of unlicensed spectrum and form Wi-Fi as part of their strategy. We describe about the commercial offloading solutions on offer by WeFi[2] and Notava[3].

WeFi

WeFi have developed ANSDF (Access Network Discovery and Selected Function) technology which is 3GPP compliant and integrates with MO's core network enabling them to monitor, control and analyze the mobile device's connectivity behavior. The WefiANSDF system consists of three parts: a software client for consumer's mobile device, a global database of Wi-Fi networks (build upon by the community efforts) and control panel that operators can use for specifying when and where devices on their network should offload. It is also possible for MOs to maintain QoS by monitoring the performance characteristics of access points through information gathered from all the users.

[2] http://www.wefi.com
[3] http://www.notava.com

Notava

Notava is a Wi-Fi offloading company providing QoS aware offloading solutions enabling MOs to manage their own and also third party WiFi networks. Their product *uAxes* integrates with MO's core network and provides them control on their subscribers over network selection. On the mobile device it is required to have *uAxes* connectivity client and connection manager. *uAxes* provides SIM based user authentication and efficient integration to operators charging and billing system as well.

2.3 Television white space spectrum opportunities

According to Olafsson et al. (2007) the spectrum that is currently being targeted for the initial commercialization of DSA-based, CR-enabled radio systems for secondary use, sharing is the TV White Space spectrum. FCC in US and Ofcom in UK have allocated TVWS for unlicensed use allowing the operation of cognitive devices on license-exempt basis. The efforts towards quantifying the availability and variability of TVWS spectrum reveal that the total capacity associated with it is quite significant. Adding on to that the wide-area coverage ability of TV frequencies (as signals in TV bands travel much further in a cluttered environment compared to in frequency bands dedicated for Wi-Fi and 3GPP technologies) and better penetration into buildings with much lower loss, TVWS becomes an attractive spectrum band to operate.

TV broadcasters are the incumbent license holders[4] of the spectrum band in concern and their cooperation is going to be central towards a successful secondary usage of TVWS. Thus in order to make sure that TV broadcasters feel motivated to co-operate, it is important that market mechanism must be such that they are also compensated in one way or the other as the operation of a cognitive secondary device in TVWS does create some kind of interference for TV broadcasting operations.

2.3.1 Origin of TV White Spaces

TV broadcasters have the license to operate in the Very High Frequency (VHF) and Ultra High Frequency (UHF) portions of the radio spectrum. Over the years the broadcasters have used the analogue transmission methods for their television services.

[4] This may not hold true for some of the market places where the broadcasters have a license to transmit only in certain places.

However in recent years the advent of digital transmission has proven to provide better user experience and higher spectral efficiency. As a result there has been a growing regulatory pressure over the broadcasters to convert their TV stations from analogue to digital transmission. Such a migration is referred to as the Digital Switchover (DSO) and has already been adopted in countries like US and UK. Due to the higher spectral efficiency of digital TV (DTV) a portion of TV analogue channels become entirely vacant after the DSO. Figure 2-3 represents the UK UHF band after the process of digital switchover.

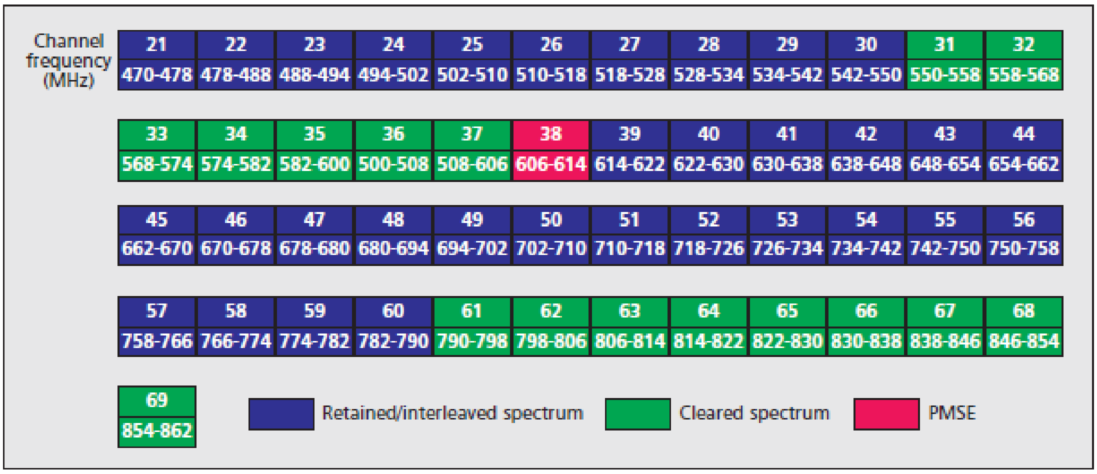

Figure 2-3 The UK UHF band after digital switchover as shown in Fitch et al. (2011)

These cleared channels are quite often misunderstood as the TVWS which they are not and are instead referred to as the digital dividend. There have been plans by the regulatory bodies such as Ofcom (Office of Communications) in UK for re-auctioning the digital dividend spectrum. However TVWS originate, as after transitioning to DTV there are typically a number of TV channels available on geographical basis which are not being used by DTV stations. These vacant TV channels are basically the guard bands and are present to avoid interference to adjacent or co-channel DTV stations. These are referred to as the TVWS or interleaved spectrum.

It is interesting to note that if the guard bands were originally deployed to avoid interference then how any other device can use it for its own transmission purpose. So the idea is to use low power devices over these locally vacant TV channels. These devices are referred to as the white space device (WSD) and because of their low power specifications they do not cause interference to co-channel and adjacent channel TV stations.

2.3.2 Quantifying the TV white space availability

Experimental modeling tools are being developed and studies (Nekovee (2010)) are being carried out in order to quantify the availability of TVWS which is primarily a function of the way TV networks are planned. However it is important to note here that there are no standard methods which have been devised on how to compute the amount of TVWS spectrum available. A number of factors are going to play a crucial role in determining how much of this spectrum could be used for the sharing purpose and identification of suitable metrics and time/spatial resolution is an important area of future research. One of these metrics is expected to be location or area of operation and correspondingly rural areas will have a higher quantity of white spaces/interleaved spectrum to offer as compared to the dense urban areas. The power level at which the cognitive radios are allowed to transmit also play an important role in quantifying the availability of TVWS. As when a high power cognitive device operates in a vacant TV channel, energy leakage to adjacent channel may cause interference to adjacent frequencies, which may be occupied. Consequently, in some future use cases, cognitive devices may be constrained not to use vacant channels whose adjacent channels are used for TV broadcasting. As shown in Figure 2-4 the available TVWS capacity for different locations in UK decreases considerably by imposing the adjacent channel interference constraint. Finally, the incompetency of existing wireless technologies to make use of white spaces available in non-contiguous fashion also restricts the access to TVWS. For example, in the case of London although a total of 96 MHz TVWS is principally available, only 16 MHz can be utilized for contiguous frequency access (Nekovee(2010)).

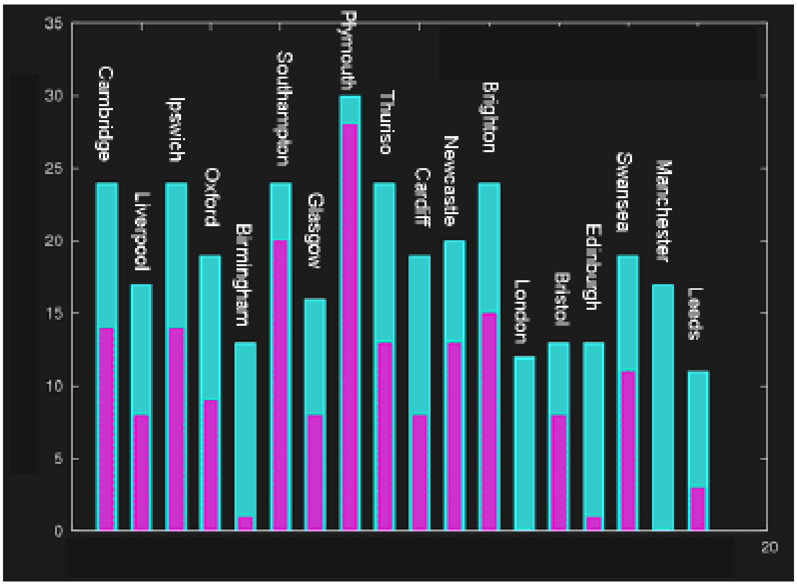

Figure 2-4 Available TVWS capacity for low-power cognitive access in 18 UK locations without (green bars) and with (red bars) adjacent channel interference constraint as shown in Nekovee(2010)

2.3.3 Standardization efforts

A number of activities are undergoing within the cognitive radio research communities and also in industry for the standardization efforts towards managing TV white spaces. We discuss a few of them (IEEE 802.11af, 802.19.1 and 802.22 and IETF PAWS) in this section.

IEEE 802.22

IEEE 802.22 is a standard for cognitive wireless rural area networks. The goal of this standard is to use CR techniques to share geographically unused spectrum allocated to the television broadcast service, on a non-interfering basis, to bring broadband access to hard-to-reach low-population density areas typical of rural environments. IEEE 802.22 WRANs are designed to operate in the TV broadcast bands while ensuring that no harmful interference is caused to the incumbent operation and low-power licensed devices such as wireless microphones.

The two methods used in IEEE 802.22 for spectral awareness are geo-location database and spectrum sensing. The 802.22 network quickly modifies its operating frequency so as to only operate on channels unused by licensed transmissions. Thus, the 802.22 network must both quickly identify which channels are allowed to use, and move to a new unused channel if the current operating channel becomes occupied by a licensed transmission.

IEEE 802.19

The purpose of this standard is to enable the family of IEEE 802 wireless standards to use TV white space by providing standard coexistence methods among independently operated TVWS networks and dissimilar TVWS devices. IEEE 802.19.1 coexistence system consists of three logical entities, coexistence enabler, coexistence manager, and coexistence discovery and information server. A logical entity is defined by its functional role and its interfaces with other IEEE 802.19.1 coexistence system entities, or external elements.

IEEE 802.11af

Usage of TVWS for enhanced type of Wi-Fi like internet services popularly known as Super Wi-Fi/Wi-Fi 2.0/White-Fi has been formalized as a new standard called as IEEE 802.11af. It is expected to provide much higher speed and wider coverage than current Wi-Fi because of the better propagation characteristics of the VHF/UHF bands and it could be understood as a wireless network with a CR-enabled access point (AP) and associated CR devices as end-user terminals.

However considering that the signals in TV bands travel much longer distance and have a better penetration into buildings thus it would cause higher levels of interference and it needs to be dealt with. Thus it is expected that the APs transmission power limits would be set at much lower levels as compared to their ISM band counterparts. The CR APs could operate in TVWS either as an unlicensed or licensed secondary device depending on the type of spectrum management framework adopted. It could either be spectrum commons approach or based on secondary spectrum markets.

Considering the unlicensed secondary devices, it is important to understand how this scenario differs from the usage of same within the ISM band. In case of TVWS the unlicensed secondary users need to make sure that the primary users are not using the spectrum if the transmission is on opportunistic basis. However in case of unlicensed use of ISM band there is no such requirement as the primary does not exist.

IETF PAWS[5]

Internet Engineering Task Force (IETF) is developing a WG called Protocol to Access White Space database (PAWS) with the goal of defining the device-database interface for TVWS database systems. According to PAWS, a WSD must access a database to get the list of available channels for its location. There could be several databases serving WSDs so that a database to database interface may be useful. However, PAWS initial work is focused in the user/device interface with the database.

Devices may be able to connect to the database directly or indirectly via the Internet or private IP networks. This interface needs to be: radio/air interface agnostic (802.11af, 802.16, 802.22, LTE etc.), spectrum agnostic (the protocol should be able to use in any spectrum band), globally applicable (applicable in any country ensuring uniformity) and it must address regulatory requirements (the interface has to be flexible to adapt to different regulatory requirements).

PAWS WG is working towards specifying both a database identification mechanism (how can a device know which database it needs to connect to) and contents of the queries and responses. This messaging between the device and the database needs to be secure (authentication, integrity of the content, etc.), requiring some authentication and security measures. The WG is still working and developing the initial proposal for the protocol.

2.4 Enabling technologies for future spectrum management

This section describes those technologies which would constitute as the building blocks for a number of architectures which have been proposed for future Dynamic Spectrum Access systems.

2.4.1 Cognitive radio

After studying the diverse ways in which the future spectrum management could be undertaken, one common feature which could be observed is the requirement of introducing cognition capabilities in the existing system. Hence a lucid understanding of Cognitive Radio concept is of prime importance as it is the underlying principle of

[5] https://www.ietf.org/mailman/listinfo/paws

technologies which are being pitched as key enablers for new spectrum management models.

We study three different definition of CR starting from the one first proposed by Mitola (who is referred o as the father of CR), then as defined by IEEE and finally by the Fedral Communications Commissions (FCC) of USA.

i. Mitola & Magurie (1999) describe the concept of CR as: “transforming radio nodes from blind executors of pre-defined protocols to radio-dominated aware intelligent agents that search out ways to deliver the services that the user wants even if that user does not know how to obtain them”

ii. IEEE P1900.1 working group (IEEEP1900 (2006)) defines CR as: “a radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and pre-defined objectives.”

iii. FCC defines CR as: “a radio that can change its transmitter parameters based on the interaction with the environment in which it operates. The majority of cognitive radios will probably be SDR but neither having software and not being programmable are requirements of cognitive radio”

CR is often referred as being frequency-agile because of its capability to transmit and receive across channels covering potentially very wide range of frequencies, even across multiple discontinuous bands. What we observe is that the definition of CR has evolved and the recent definitions given by IEEE and FCC have gone narrower in scope primarily corresponding to radio systems having adaptive spectrum awareness. Such systems are going to be based on configurable radio platforms such as SDR. Looking at the current CR devices developed by various research groups and industry players, we find that majority of those are based on SDR technology.

2.4.2 Software defined radio

Tuttlebee (1999) defines SDR as: “technology wherein software modules run on a generic hardware platform consisting of digital signal processing (DSP). It enables on-the-fly reconfiguration of radio characteristics, such as frequency modulation, power and waveform, and allows the same hardware to be reconfigured for use in different parts if the radio spectrum”**.** As prevalent with any other CR technology prototyping, standardization and commercialization of SDR technology is still at an early stage and is currently facing challenges such as high power consumptions, high processing power requirements and high initial costs.

The European Telecommunications Standards Institute (ETSI) Reconfigurable Radio Subsystems (RRS) working group has a separate SDR related standardization work for base stations and the mobile devices. ETSI RRS considers mobile device SDR as the underlying implementation technology and enabler for CR (Mueck et al. (2010)). It has identified a set of capability requirements for SDR equipments as highlighted below:

i. Multiradio configuration capability: SDR equipment in mobile device is expected to install, load and activate a radio application while running a set of radio systems already.

ii. Multiradio operation capability: SDR equipment in mobile device is expected to execute a number of radio systems simultaneously by taking into account temporal coexistence rules designed for their common operation

iii. Multiradio resource sharing capability: SDR equipment in mobile device is expected to execute a number of radio systems simultaneously by sharing computation, memory, communications and RF circuitry resource available on the radio computer platform by using appropriate resource allocation, binding and scheduling mechanisms.

2.4.3 Cognitive radio networks

A cognitive system for accessing radio spectrum is not going to be composed of a single cognitive radio but instead a number of CR entities are going to operate in a networked architecture. Thus it brings out the need to study the CR network architecture in detail. CR networks can be divided in two groups, the primary network and the cognitive network. The primary network is a licensed network that has exclusive right to access to a specific frequency band. Cognitive networks do not have a license to operate in the desired band, and is often referred to as the secondary network.

As defined in Thomas et al. (2006), the fundamental components and architecture of a CR network includes the following –

- Primary User: A primary user has a license to operate in a certain spectrum band. Its access can be only controlled by the base-station and should not be affected by other unauthorized users.

- Primary Base-Station: Primary base-station is a fixed infrastructure network component with a spectrum license. Sometimes, primary base-station may require both licensed and CR protocols for the primary network access of CR users.

- Cognitive Radio User: is an unlicensed user, so the spectrum access is allowed only opportunistically. The CR user should have the capabilities of spectrum sensing, spectrum decision and spectrum mobility. It has to be able to communicate with other CR users apart from the base-station.

- Cognitive Radio Base-Station: CR base-station is a fixed infrastructure component with CR capabilities. It provides single hop connection to CR users without spectrum access license.

CR users can communicate both with the base stations and other CR users and as a result there are three types of access networks possible – Cognitive Radio Network Access (occurs when a CR user access its own base station), Cognitive Radio Ad Hoc Access (occurs when CR user communicates with other CR user through an ad-hoc connection) and Primary Network Access (occurs when a CR user access the primary base-station through the licensed band).

2.4.4 Database systems

Before discussing details of database system as enabling technology for future spectrum management models, we would like to mention about sensing which is going to be important for non cooperative DSA systems involving opportunistic usage of spectrum. Sensing techniques would be required by CRs to monitor and sense the available spectrum bands in order to detect the spectrum holes or free portions. Akyildiz et al. (2006) describe a number of sensing methods such as primary transmitter detection, primary receiver detection and interference temperature management. Since we are focusing on cooperative DSA, understanding of different database systems and their architecture holds more importance as compared to sensing technology.

A database system provides an alternate to sensing technology for enabling CR kind of operation. Geo-location technology plays an important role in this system as it is required for an unlicensed device to determine its location (using a GPS receiver) and report it while accessing the database. In fact according to US FCC Second Report and Order (R&O) in which the TV white spaces have been allocated to unlicensed use allowing the operation of cognitive devices on license-exempt basis, database system has been set as a primary tool for interference management. In UK on the other hand, Ofcom has proposed a use of both database system and sensing techniques. Having gauged the current policies being adopted by regulatory bodies and efforts being put in by the industry players, geo-location database seems to be the most important mechanism in providing a technically feasible and commercially viable solution (at least in short-term) for white space spectrum detection, primary user protection, agile transmission techniques, and the etiquette protocols for intra- and intersystem coexistence in TVWS (Fitch et al. (2011), Nekovee (2010)).

Ofcom lists down five key issues which must be addressed when implementing a database system:

- What kind of information is required from a CR device to database(s)? : Parameter such as device location is essential. Device type, preferences etc. could also be provided.
- What kind of information is going to be returned from the database(s) to the device? : A list of vacant channels and allowed transmit power levels for the geographical location in consideration.
- How often the database(s) needs to update its information and hence the periodicity with which CR devices will be required to re-consult? : According to Ofcom recommendations, devices should consult the databases every two hours. We have also tried to answer this question using our simulation model which will be discussed in the chapter focused on results obtained from evaluation of market mechanism design.
- What are the modeling algorithms and device parameters to be used to populate the database(s)? : There are some recommendations depending on the transmission model, device sensitivity, methodology etc.

- Who and on what terms should be responsible for the maintenance of the database(s)? : Depending upon different value network configurations there are a number of possibilities.

In order to calculate the white space distribution over the frequency bands, the database need parameters and information such as primary user's operating frequency, transmitted power, size and type of transmit antenna etc. These parameters are provided to the database system by primary users. A secondary user has an access to a database system for getting information about the primary users in a given area. The secondary users interact with the database to know which frequencies are free at certain time and in a certain location and determine the maximum transmission power they are allowed to use as set by the regulatory/standardization bodies.

Hence in order to construct a TVWS DSA system, information regarding TV transmitters and radio microphones can be registered in a database, and then a GPS enabled white space device can query the database periodically to find out the availability of vacant TV channels in a specific area and time. According to Borth et al. (2008) the TVWS system can use standard propagation models to ensure that the CR devices are outside the protected operational contour of the incumbent system before it starts operating in the channel. Now from the perspective of secondary user i.e. a WSD there are two important issues which need to be addressed. First being the requirement to provide WSD with an additional internet connectivity source to access the database information. Secondly, since WSDs are required to provide their accurate location information to database and they make use of GPS technology for this purpose thus it is required to identify a novel solution to counteract the problem associated with poor performance of GPS receivers in an indoor environment.

In context of database centric DSA system, Master-Slave architecture for white space devices has been proposed by various standardization bodies. Under this configuration a master device connects to the database to obtain a set of available frequencies in their area and the slave devices obtain information about the vacant channels from the master devices. Thus a slave device does not need to contact the database on its own as it is completely managed by its master. The radio network in the white space is created by the master device which can be an access point that establishes a Hot Spot coverage, a base station that establish cellular coverage, or a device that establish a peer-to-peer or ad-hoc network (IETF PAWS). An alternate source of internet connectivity is required for the master device through which it can send a query message to the database and get information about any available vacant channel.

Different database structure

We have already discussed a possible Master-Slave architecture which the WSDs are likely to adopt in order to realize the commercialization of TVWS usage. Now we review ideas of different database structure as proposed in research literature and by different industry players in response to FCC call for acting as database administrators.

As the proposals of TVWS usage include the possibility of operation by either an unlicensed or a licensed secondary system, we discuss here the database structure in accordance to the type of secondary usage. It is interesting to note that in both the scenarios a consensus is being reached on using a two tier approach – a centralized database entity aided by a number of locally distributed secondary databases. Such a two tier approach is important for the reason of accurately knowing the location of WSDs which is an important input for the algorithms (running in central database) to calculate TVWS channels and the powers that could be safely used without causing interference to primary users. In case if we make use of a single database only then it is possible that the master and slave devices are at different locations which could result in inaccurate information on availability/non-availability of TVWS channel. Moreover a single tier database approach would result in an overly conservative allocation of channels and transmit powers.

I. Database architecture under licensed and unlicensed usage of TVWS

First we discuss the usage of TVWS for adapting 3GPP radio standards such as LTE for operation in UHF white space bands. Mueck et al. (2010) describes a possible structure of database driven access to TVWS by multimode user terminals (terminals supporting multiple radio access technologies). These terminals are assumed to have the capability of accessing TVWS spectrum bands in order to provide wireless broadband access. The entities involved in such a system are going to be - a tier 1 Central Database containing information about the available vacant TV channels, a tier 2 control point local in nature and closer to the e-NodeB (base stations) corresponding to the geographical area in concern and finally the multimode user terminals connected to their respective eNodeB. This architecture has been illustrated in Figure 2-5.

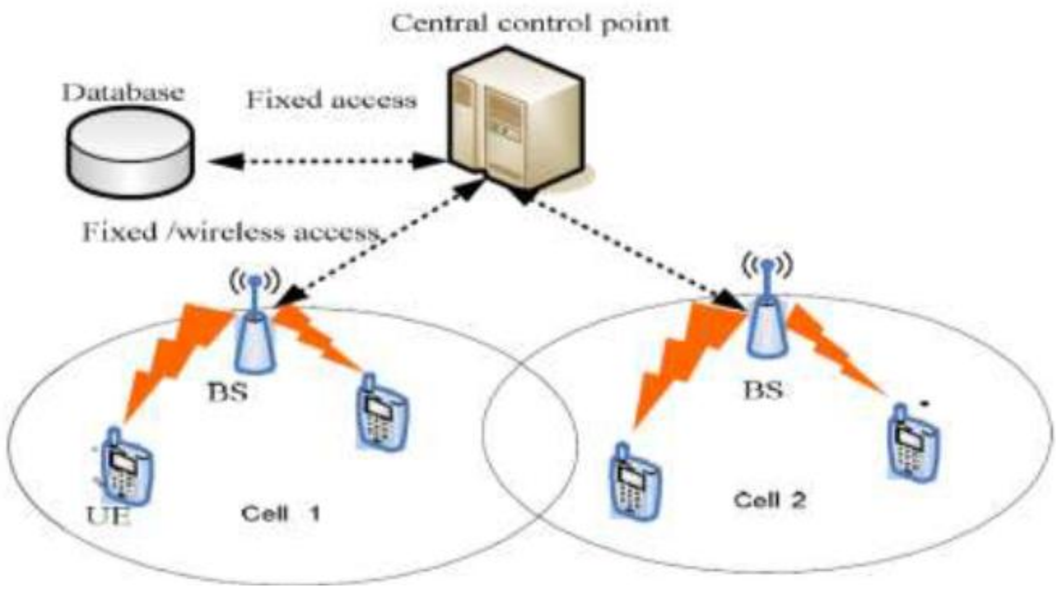

Figure 2-5 Database driven access to TVWS as seen in ETSI RRS as described in Mueck et al. (2010)

Here the relation between eNodeB and user terminals is similar to that of Master-Slave architecture discussed for the case of WSDs in previous section. After gauging a capacity crunch and a requirement to access more spectrum, eNodeB sends TVWS allocation request to a central control point as shown in Figure 2-5. Being closer to eNodeB, a control point can determine eNOdeB's location with more precision. The control point then inquires the database for availability of TVWS frequency bands at the location of eNodeB. If available, the control point sends back TVWS allocation response to eNodeB which further notifies the user equipments (UEs) about the information of allocated TVWS. The concerned UEs change their operating frequency to the allocated TVWS frequency and this information is conveyed by eNodeB through the control point to the database so that it can update its list of TVWS availability.

Next we shift our focus for database structure in the case of unlicensed secondary usage of TVWS. Fitch et al. (2011) describes a two-step database approach which is being developed for a European FP7 project QoSMOS and its architecture is illustrated in the Figure 2-6.

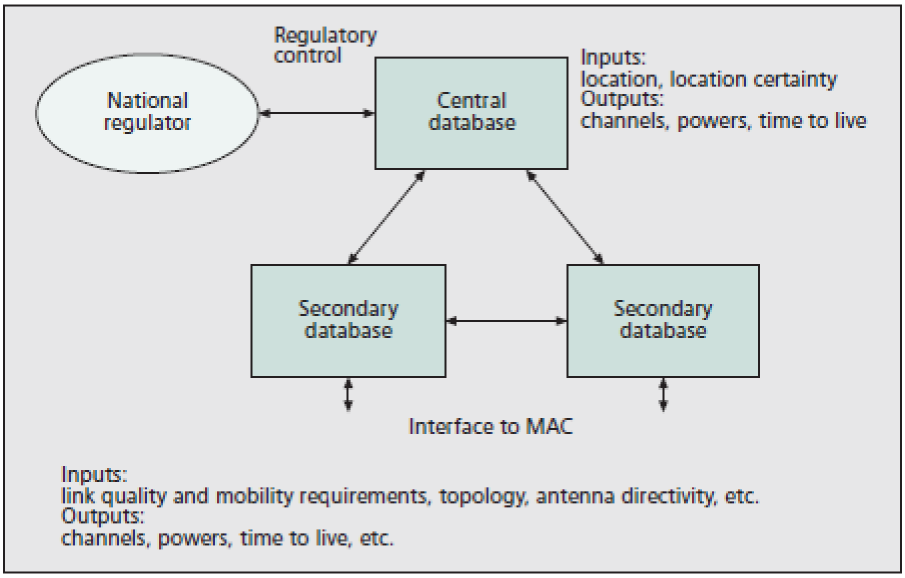

Figure 2-6 A possible two step database structure for unlicensed secondary usage of TVWS as described in Fitch et al. (2011)

As per this structure, the secondary database would contain more accurate information about the location of the white space devices. It would also have detailed knowledge about the system topology such as antenna directives, and the QoS and mobility needs of the individual radio links. All this information would result in a more efficient brokering of spectrum portfolio from the central database which means a wider choice of channels and higher transmit powers available for WSD usage.

II. Google database architecture

In order to facilitate rapid development of wireless networking protocol in white spaces, earlier this year FCC in US had approved and assigned responsibility to nine companies for developing and administering white space databases. Amongst these companies were the internet giants like Google and Microsoft. Google has been one of the strongest advocates of white space wireless as it considers this technology a way to rapidly spread access to the web. The following Figure 2-7 illustrates the database architecture as proposed in Google (2009).

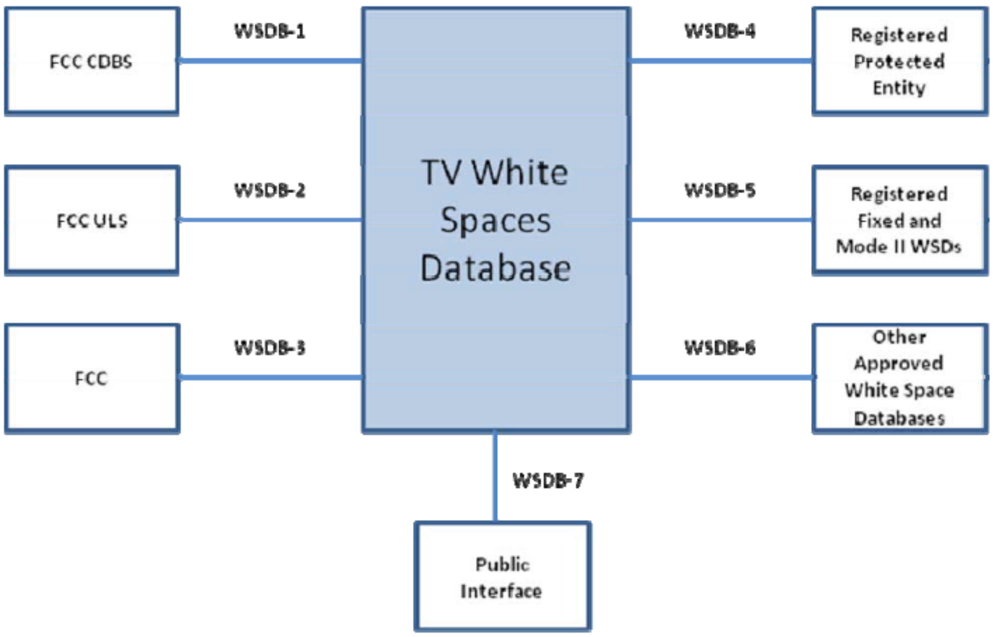

Figure 2-7 Google database structure as described in Google (2009)

Google proposes a flexible and market-driven approach, without posing any limits on the number of database providers and correspondingly their database architecture specifications. Google from the outset have supported an open architecture model for the database. As seen in the figure, a number of interface (WSDB1 – WSDB7) have been defined to its database where each interface has a well defined function. WSDB-1 and WSDB-2 are used for directly connecting to FCC Commission's Consolidated Database System (CDBS) which contains information regarding the location and channel of protected primary entities such as DTV stations and information about location and identification of secondary WSDs (geographical location, FCC ID serial number etc.). WSDB-3 is used for general purpose communication with FCC. In order to get the available channel list, the WSD will connect the database through WSDB-5 to register in the database. The database will calculate the available channels and return a list with them to the WSD. Interference is avoided by protecting the TV stations using the information fetched from WSDB-1 and WSDB-2 interface. According to Google anyone should be able to have an access to the available TV channel list. The WSDB-7 interface will offer public access to non-confidential information from the Database. Since Google plans to cooperate with other database administrators in order to exchange the information for better decision making in TVWS calculations, it has introduced another interface WSDB-6 for this process. Other database administrators such as the Spectrum Bridge have also adopted similar database architecture.

III. COGEU database architecture

COGEU is an EU FP7 project to develop Cognitive radio systems for efficient sharing of TVWS in European context. Unlike regulatory bodies such as FCC and Ofcom which are only working towards developing an opportunistic DSA model to support unlicensed secondary usage of TVWS, COGEU also aims to develop DSA system that leverage the value of underutilized spectrum through the introduction and promotion of real-time secondary spectrum trading. Thus according to COGEU D3.2 (2010), TVWS must be assigned in an optimal manner for unlicensed use by WSDs (spectrum commons approach) and for trading use to the spectrum broker (secondary spectrum market approach).

As per the COGEU analysis, geo-location database driven access to TVWS is particularly relevant with regards to current regulatory/standardization efforts and they have identified two scenarios involving the usage of database for the protection of incumbents. First one being the usage of geo-location database coupled with spectrum sensing and the second one involving only geo-location database access. The second scenario is of more importance for our market mechanism design as it talks about combination of unlicensed access to TVWS and also the secondary spectrum markets facilitated by the spectrum broker. The following Figure 2-8 illustrates the different interfaces involved in proposed database architecture.

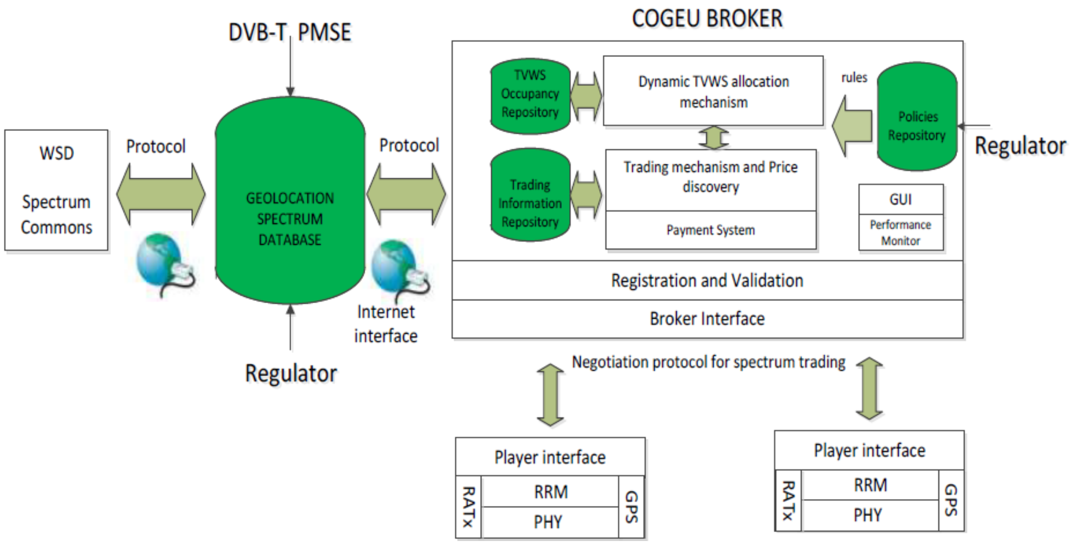

Figure 2-8 TVWS access database architecture according to COGEU as described in COGEU D3.2 (2010)

The architecture involves the usage of different kind of repositories which are the contact points of information during the whole functioning of secondary spectrum usage. These repositories include that of geo-location spectrum database, broker internal repositories (TVWS occupancy repository, trading information repository and policies repositories).

The coupling of database and cognitive radio allows for optimal use of radio spectrum and this mechanism is sufficient for successful and productive implementations of various applications in TVWS. Thus what is required is efforts from the regulatory bodies and industry players to develop a successful database capable CR technology in TVWS. FCC in US recently announced that it will conduct a test of the database of broadcast frequencies which will be used for the wireless networking protocol known as white space networking. The database for the test was designed by Spectrum Bridge, one of the nine companies the FCC chose to manage the system.

Commercial deployments of TVWS database

There have already been some commercial deployments of database driven usage of TVWS. We present two of such examples, one being the Microsoft WhiteFiServices and the other one being that of Spectrum Bridge in this section.

I. Microsoft WhiteFiService[6]

Microsoft has created WhiteFiService, a research platform to plan a white space network. It provides APIs that wireless devices can use to determine the available white spaces in a given location. The data about primary transmitters (tower location, TV channel, transmit power, antenna height etc.) are provided by the FCC Commission's Consolidated Database System (CDBS) and the data about the terrain from NASA. The attenuation from the transmit tower is calculated following some algorithms. In this way, with the device location as input data, WhiteFiService provides the available channels in that location.

II. Spectrum Bridge[7]

Spectrum Bridge is a company that provides wireless networks with an ability to dynamically access the available spectrum via a database system. It tested an experimental White Space Database system for the FCC in January 2009 and has been operating a complete online white space solution since January 2009.
Spectrum Bridge already has several commercial or at least real-state implementations like Smart Grid TVWS network and TVWS broadband network in collaboration with companies such as Google, Plumas-Sierra Electric Cooperative, Dell etc.

2.5 Spectrum trading markets

Spectrum trading markets provides solution to the problem where a user has a sudden unanticipated need for spectrum which is not being fulfilled, while there exist other spectrum users in the area having idle spectrum. What is required is an organized market with well defined procedures which can bring together buyers and sellers to benefit for all.

Song et al. (2009) gives an analysis of incentives to spectrum trading from both macro and micro perspective. Amongst the macro factors it lists the changes in demand, technology and policy the most important ones and the micro factors include inefficient initial spectrum allocation approach and a possible change in service strategy by service providers. Spectrum trading can vastly improve the spectrum utilization levels by allowing the licensees to be those who value its use the most and by making use of the

[6] http://whitespaces.msresearch.us/
[7] http://www.spectrumbridge.com/WhiteSpacesSolutions/showmywhitespace.aspx

technology that provides the best economic gains. Competition among service providers is also likely to increase under a market supporting spectrum trading. It would make it easier for the new and innovative companies such as Google and Apple to get an access to spectrum. This would also stimulate technological innovations since there would be interest to have intelligent SDR or cognitive radio based systems to make as much use of tradable spectrum as possible and offer services over it (Caicedo & Weiss (2007)). ST markets would also help end-users in getting freedom from getting locked to a specific service provider and a specific wireless standard. Caicedo (2009) says that users can choose and join a service provider with best possible network available at any time and geographical location.

2.5.1 Challenges to overcome for successful ST markets

Success of ST markets depends upon overcoming numerous challenges posed on technical, economical and regulatory front. Tonmukayakul & Weiss (2004) argues that central to the issues are the effects of transaction costs associated with leasing. Transaction costs depend upon technical factors (flexibility in usage of wireless service over traded spectrum, application requirements and advancement in the CR technology), economic factors and also different forms of spectrum sharing. Bykowsky (2003) supports the above argument by saying that the success of secondary markets for trading of spectrum will depend upon the ability of trading mechanism to minimize transaction costs. Crocioni (2009) also identifies high transaction costs as an important factor which may result to inefficient trading within the markets. Another factor which has been considered as an impediment to the success of ST markets is the low spectrum trading activity, the main reason of which is attributed to lack of liquidity in such markets. Bykowsky (2003), Chapin & Lehr (2007) discusses several steps to enhance market liquidity. Chapin & Lehr (2007) identifies that there are three enablers for market liquidity: available spectrum, customer demand, and low transaction costs. Interference management in ST markets also requires special consideration as increased interference between various services operating in a ST market will have negative effects on end-user experience. Caicedo & Weiss (2011) and Crocioni (2009) also point out that the spectrum markets can be viable if sufficient number of market participants exists and the amount of tradable spectrum is balanced to the demand.

According to Caicedo & Weiss (2007) It gets even more complicated if we are trying to develop a heterogeneous market place which involves co-existence of more than one wireless standard (a multi-protocol wireless architecture)in a spectrum trading area. Thus, the tradeoffs of managing several standards versus restricting their number to only a few should be carefully analyzed in a ST environment.

Caicedo & Weiss (2007) gives a classification of technical architecture for the implementation of spectrum trading. Infrastructure, configuration methods, activation and flexibility are the key elements which have been identified for the classification purpose. It argues that the choice of architecture would determine what kind of possible interactions could occur from the technical viewpoint. Also different architecture would require a different set of technical elements, protocols and capabilities for implementation which will have consequences in terms of information flows. The following table as given in Caicedo & Weiss (2007) summarizes the classification in terms of different technical configuration and its impact on the functioning of spectrum trading –

Table 2-2 Classification of technical architecture for implementation of spectrum trading done in Caicedo & Weiss (2007)

<table>
<tr><th></th><th>Categories</th><th>Comments</th></tr>
<tr><td rowspan="2">Infrastructure</td><td>Shared</td><td>Infrastructure costs for each provider would be reduced but optimal placement/coverage may not be achieved.</td></tr>
<tr><td>Not Shared</td><td>Placement/coverage goals are easier to fulfill but at a higher cost.</td></tr>
<tr><td rowspan="2">Configuration</td><td>Centralized</td><td>Flexibility is limited to those protocols that the central exchange allows and is able to configure</td></tr>
<tr><td>Distributed</td><td>Allows for high flexibility in providing several wireless protocols over a region</td></tr>
<tr><td rowspan="2">Activation</td><td>Provider initiated</td><td>Requires a configuration channel from Base Stations (BS) to Mobile Node (MN)</td></tr>
<tr><td>Provider + user initiated</td><td>Requires configuration channels to support BS to MN and MN to DB requests</td></tr>
<tr><td rowspan="2">Flexibility</td><td>Multi-protocol</td><td rowspan="2">As fewer protocols are supported, interference prediction and control improves</td></tr>
<tr><td>Single protocol</td></tr>
</table>

With our objective of developing a heterogeneous ST market model, configuration and flexibility are two vital parameters for architecture design. As seen from table above both of them are closely interlinked and determine whether the usage of multiple wireless standards over a ST region is possible or not. Hence what we aim for is a distributed technical architecture with a flexibility of using multiple wireless protocols.

2.5.2 Analogies with other trading markets

During the past decade, the electric utility industry has been using a spot market in electric power to match supply and demand on an hourly basis. Nord Pool Spot [8] runs the leading power market in Europe.

The spectrum markets based on spectrum trading could also be considered a spectrum management framework resembling financial markets used for trading of financial instruments (such as stocks, bonds) among investment banks, hedge funds etc. These markets are secondary in nature in the same sense that stock exchange is a secondary market. In equities, the primary market is the Initial Public Offering (IPO) whereas in spectrum the primary market would be an auction or beauty contest (Weiss & Lehr (2009)). According to Kasbekar et al.(2010) just as in secondary financial markets, ST markets would not only allow the trading of raw spectrum (bandwidth), but also of different kind of other services (such as Wi-Fi capacity) derived from the usage of spectrum (for example the unlicensed ISM band). However the financial market's stock trading mechanism cannot be entirely adopted as it is for the ST markets owing to the difference in nature of radio spectrum from stock market commodities. The most important challenge to counter is how a tradable commodity can be constructed given that spectrum at different frequencies (and their availability for use at different location and times) is not identical in its specifications. Spectrum usage must satisfy certain temporal and spatial constraints that are unique. For example, simultaneous operation in adjacent frequency bands is bound to cause interference in neighboring locations; however it is not an issue for geographically disparate locations.

2.5.3 Different spectrum trading mechanisms

Various framework and mechanism which would facilitate in accomplishing ST markets have been discussed in the research literature. According to one of the

[8] www.nordpoolspot.com

framework as discussed in Barrie et al. (2010), ST markets are visualized as two tier markets, the upper tier consisting of spectrum owners that trade spectrum assets analogous to land rights (selling and buying of spectrum usage rights for long durations – months/years), and the lower tier comprising of spot markets where spectrum owners lease out spectrum for small durations (hours/days) at specific locations. Thus upper tier adopts the DSA model based on cooperative primary sharing while the lower tier adopts the cooperative secondary sharing model.

Analysis done by Yoon et al. (2010) suggests that secondary trading methods could be based on three different mechanisms – auctions, direct trading and a brokerage system. All these different spectrum trading mechanisms form the basis while designing our market mechanism for secondary usage of spectrum.

I. **ST model based on brokerage system:** In this model, the broker manages the trading information in between the spectrum users. Its primary task is to match the buyers and sellers in an optimal manner for which it receives a brokerage fee for every matched trade. Generally the commission is decided to be a fixed percentage of total value of trade. Brokerage architecture has been mainly focused on computer network systems such as the grid network.

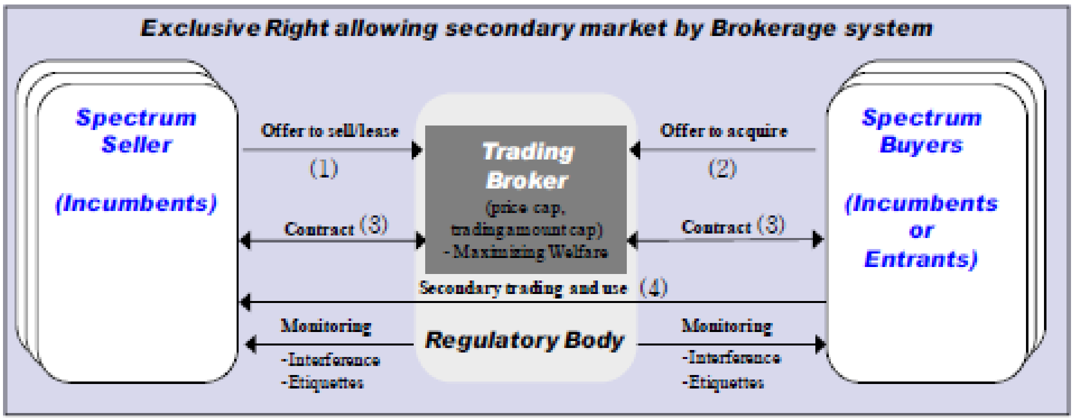

Figure 2-9 Framework for secondary trading market by broker as described in Yoon et al. (2010)

Chapin & Lehr (2007) illustrate the emergence of new intermediaries within a DSA marketplace. One such new intermediary most likely to emerge is a Broker as expected in a trading scenario. A broker would insure market liquidity and low transaction costs considered to be key elements for a viable trading market. Chapin & Lehr (2007) brings out a possibility of three different categories of spectrum brokers.

a) Simple spectrum broker – which has a simple task of matching buyers and the sellers
b) Spectrum distributor type 1 – has a role of delivering QoS-differentiated spectrum access to the Service provider
c) Spectrum distributor type 2 – in addition to above specified roles; it also takes the responsibility for the safety of secondary spectrum access. It may install and operate the system required to determine when secondary operation in a given band and at a given location is safe.

The following Figure 2-10 illustrates the three different categories of spectrum brokers as visualized by Chapin & Lehr (2007)**.**

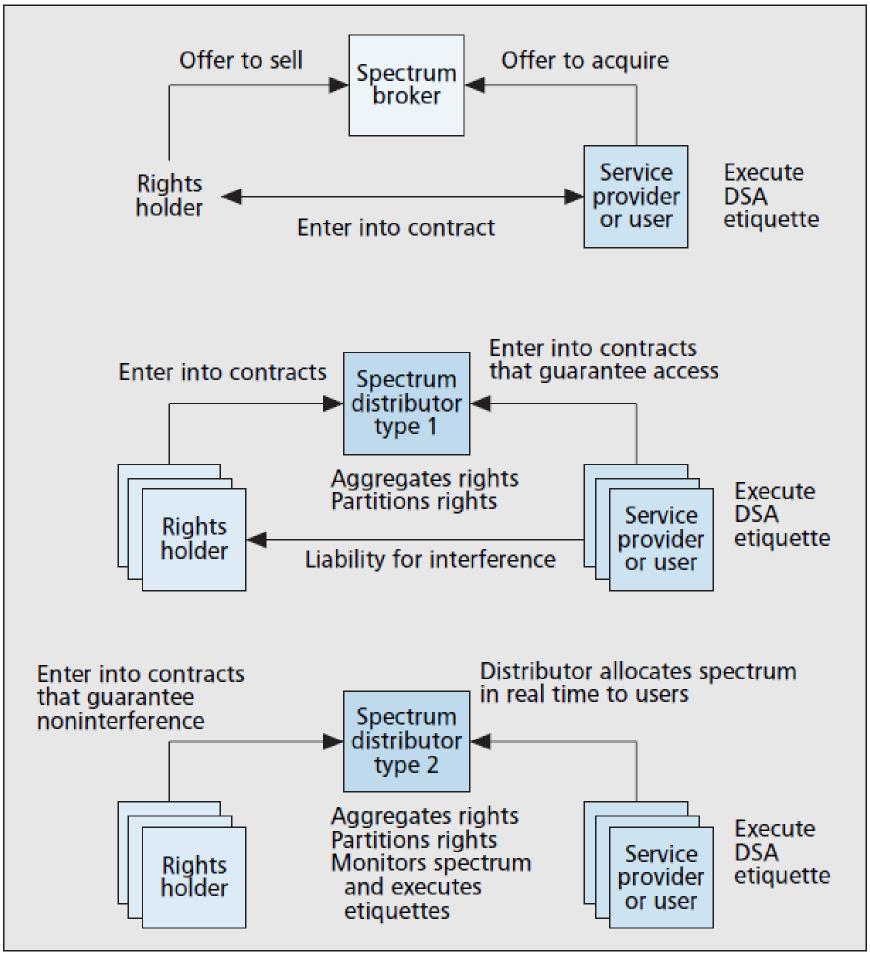

Figure 2-10 Different categories of spectrum brokers as described in Chapin & Lehr (2007)

As we are attempting to construct a DSA market place involving heterogeneous radio access technologies. The above described different types of spectrum brokers could be mapped to various possible market scenarios. For example in the case of business model involving offloading the mobile data traffic to Wi-Fi APs, a variation of first kind 'Wi-Fi capacity broker' could be efficient. The main reason being that the unlicensed frequency band can't assure any kind of QoS and thus a task of the broker would be no more than being a mediator between the demand and supply side. However when we consider the spectrum sharing or trading in TVWS, issues pertaining to QoS and interference avoidance can assume a more important role and hence would require a Spectrum distributor of Type 1 or 2 as a mediator.

II. **ST model based on auctions:** Under this mechanism, spectrum buyers procure the required spectrum from the sellers through an auction trading process. The role of spectrum auctioneer could be assumed by a government organization (regulatory bodies) or private spectrum exchange acting as a third party.

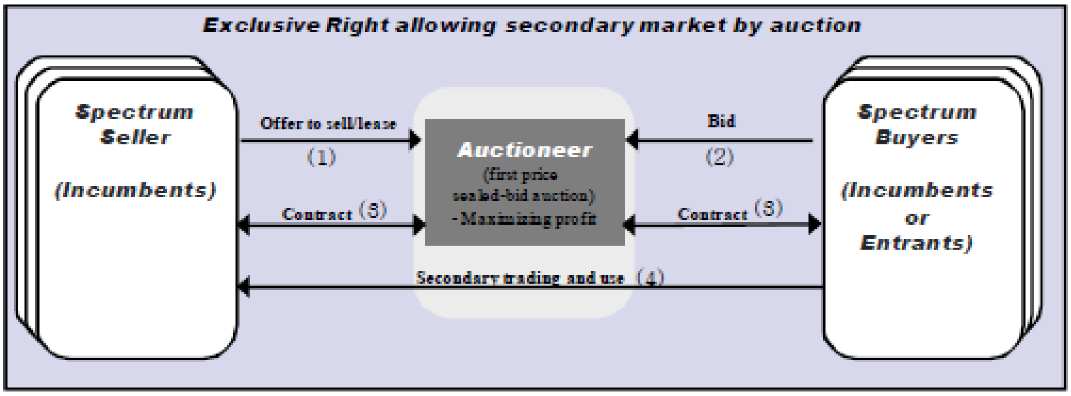

Figure 2-11 Framework for secondary trading market by auction as described in Yoon et al. (2010)

III. **ST model based on mutual trade (Direct Trading):** In this mechanism no third party is involved between the sellers and buyers. The trade happens based upon mutual agreement of leasing cost and time. An alternative way of looking at this model is to consider it as a revenue sharing mechanism where the secondary user shares a fixed percentage of it revenue with the primary user.

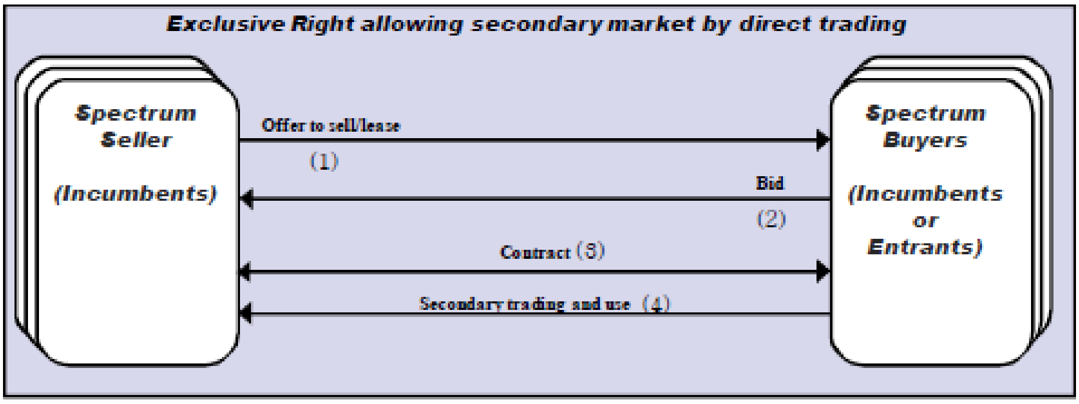

Figure 2-12 Framework for the secondary trading market by direct trading as described in Yoon et al. (2010)

2.5.4 Spectrum Trading Markets evaluated using Agent Based Modeling

The research literature on the simulation and evaluation of spectrum trading markets is very sparse. There have been few efforts to simulate the markets using the concepts of agent based modeling and we present those in this subsection.

Caicedo & Weiss (2011), Chu et al. (2010), Yoon et al. (2010), Tonmukayakul & Weiss (2005) have used ABM for simulating and addressing different challenges associated with ST market. Caicedo & Weiss (2011) uses ABM for providing guidelines regarding the number of market participants and the amount of tradable spectrum required in ST market to make it viable. Given their modelling parameters they found that a minimum of six active participants were necessary for making the ST markets viable. Using ABM Yoon et al. (2010) analyses three different mechanisms – a brokerage mechanism, auctions and direct trading; on which ST markets could be based upon. According to Yoon's model direct trading provides a more active market with or without regulation.

Tonmukayakul & Weiss (2005) develops an agent-based spectrum access model to examine the pre-conditions required for successful emergence of ST market. Chu et al. (2010) propose an agent-based spectrum trading model to address the challenge of finding the most profitable strategy of agent(s) when spectrum demand is uncertain. Prior research work on ST markets using ABM reveals that it could be used to study both economical and technical aspects of the spectrum sharing.

3. Market mechanism evolution

As seen in previous chapter, studies focusing on improving the efficiency of spectrum usage have received much attention and a number of different spectrum management models have been proposed. Based on our objective of creating an economically favorable scenario for all the spectrum users we decide to go forward with ‘market model’ amongst all the discussed future spectrum management models.

The literature on applying trading mechanisms to spectrum management has been expanding steadily; however the existing research on spectrum trading market simulations primarily concentrates on scenarios involving homogeneous market actors where the participating players use similar radio access architecture (one wireless standard). This simplifies the trading phenomena by making interference management and other potential challenges associated with spectrum trading easier to cope with. Through our market mechanism we try to build a generic secondary market which also facilitates trading in between heterogeneous market actors. Thus in this section we will propose how secondary spectrum trading markets are going to emerge and what role the existing as well as new market actors are going to play in its emergence.

For the success of DSA services, Chapin & Lehr (2007) has already argued that the liquidity of spectrum in the market plays a very crucial factor. Further it lists down availability of spectrum as one of the key enabler of liquidity. Our market mechanism takes an evolutionary approach on similar lines as discussed regarding the factors affecting the availability of spectrum in Chapin & Lehr (2007). Since we have adopted incremental approach as a central theme for designing our market mechanism thus we assume that the following incremental steps will happen in the evolution process towards the realization of secondary spectrum trading markets:

Step 1 Wi-Fi Capacity Market
Step 2 Super Wi-Fi Capacity Market
Step 3 Spectrum Leasing Market

According to Chapin & Lehr (2007) the success of DSA services must be first demonstrated with their initial deployment in the simpler bands where the spectrum access etiquette required is less complex in nature and as a next step DSA must be extended to other spectrum bands where there are strict requirements of protecting the incumbent primary users. The evolutionary approach which we adopt for our market mechanism finds resonance with this argument. Adopting such a strategy would help in maintaining a step-wise increase in availability of spectrum over time which would ensure the liquidity of spectrum required for market success.

Wi-Fi capacity market represents initial step in this direction and thus we will first design the case of capacity trading in ISM band which are available to use on unlicensed terms and with minimum set of restrictions. Next we move over to the scenarios demonstrating the realization of trading markets for TVWS based on either local area or wide area strategy. As per local area strategy, Super Wi-Fi capacity trading markets are introduced where Wi-Fi operators operating in TVWS act as secondary users. Then under wide area strategy TVWS spectrum leasing markets are introduced where MOs operating on a contiguous band of TVWS act as secondary users. The necessity of protecting the TV broadcaster's transmission against interference makes the operation of trading markets more complex in TVWS as compared to that in ISM band. Later in this section we will introduce the modeling tool used for evaluating the designed mechanism and will also discuss the intricate details involved in setting up the model (i.e. market assumptions and model configuration).

3.1 Value network design

We make use of value network configurations to illustrate the working of different spectrum trading scenarios. Under this VNC scheme, we adopt the representation of different technical component, their role and corresponding actors undertaking those roles from Casey et al. (2010) as shown in Figure 3-1. Technical components interact through their technical interface while actors have their business interface for interacting with other market actors under different trading scenarios.

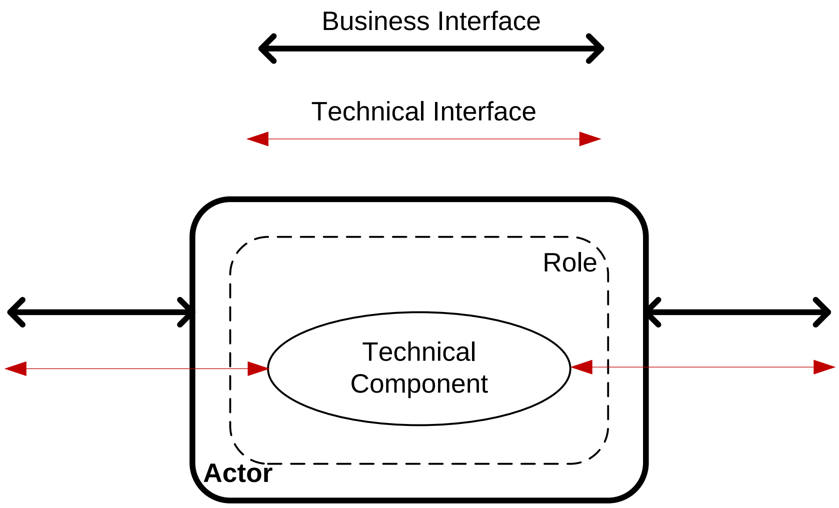

Figure 3-1 Representation for technical component, role, actors and different interfaces adopted from Casey et al. (2010)

The following Figure 3-2 illustrates the value network design of our market mechanism. This figure is an all inclusive one since it illustrates the functioning of each incremental step we have assumed to happen in the evolution process towards the realization of secondary spectrum trading markets. It is important to note here that our market mechanism is mobile operator centric since we have assumed that only MOs have a subscriber relationship and it does not exist for any other market player. As per this assumption we only model the data demands of MO's subscribers which represent a valid argument considering that demands for mobile broadband has been growing exponentially and as a consequence of which MOs are most likely to search for new capacity and spectrum resources. The incremental steps towards the realization of spectrum markets and the actors participating in each of those steps are described in the following sub-section.

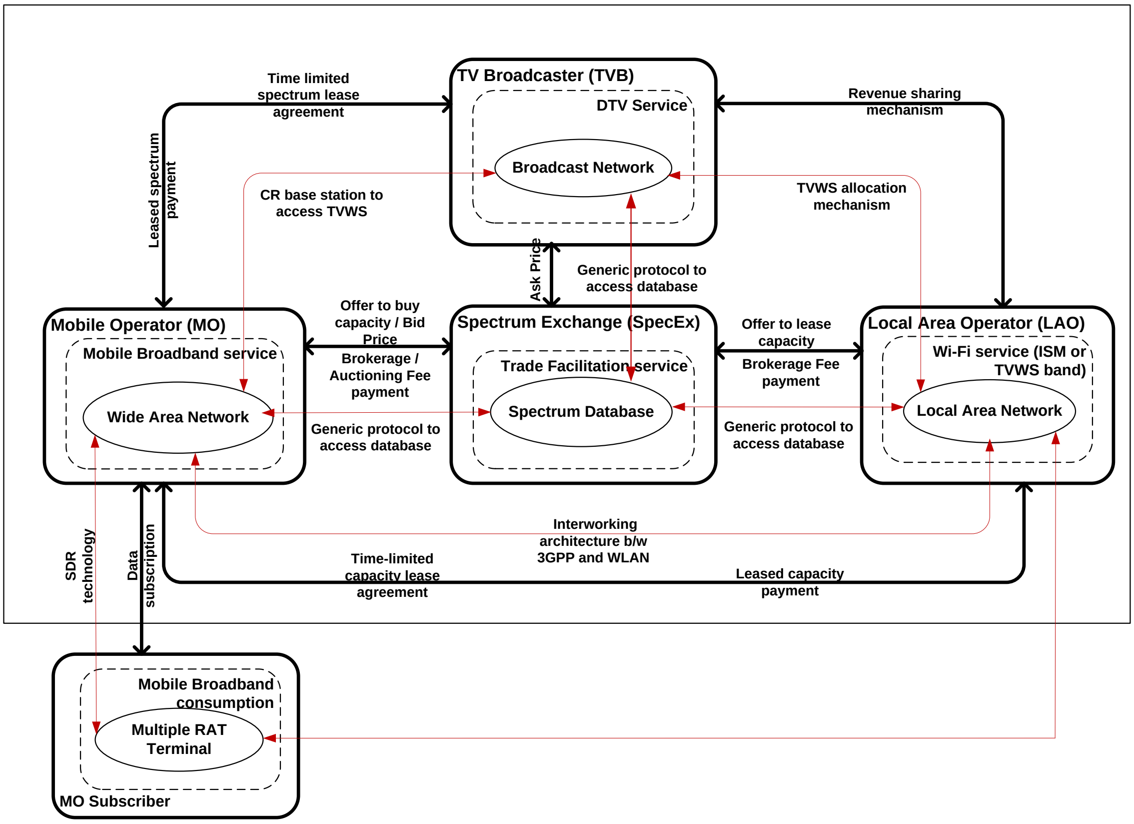

Figure 3-2 Value Network Design of market mechanism illustrating all incremental steps towards secondary spectrum trading markets[9]

3.1.1 No trading market scenario description

We begin with a scenario (Base case) which depicts the current market situation and it involves the participation of MOs, LAOs and MO subscribers as shown in Figure 3-3. The primary role of MO has been defined as that of providing mobile broadband services to its subscribers. It is also assumed that MO's network infrastructure has cognitive capabilities in terms of cognitive base stations, support for SDR technology, spectrum sensing etc. for realizing DSA systems when required.

[9] Note that a box enclosing all the market actors except MO subscriber denotes the simulated part of market mechanism. MO subscribers have not been modeled explicitly within our model.

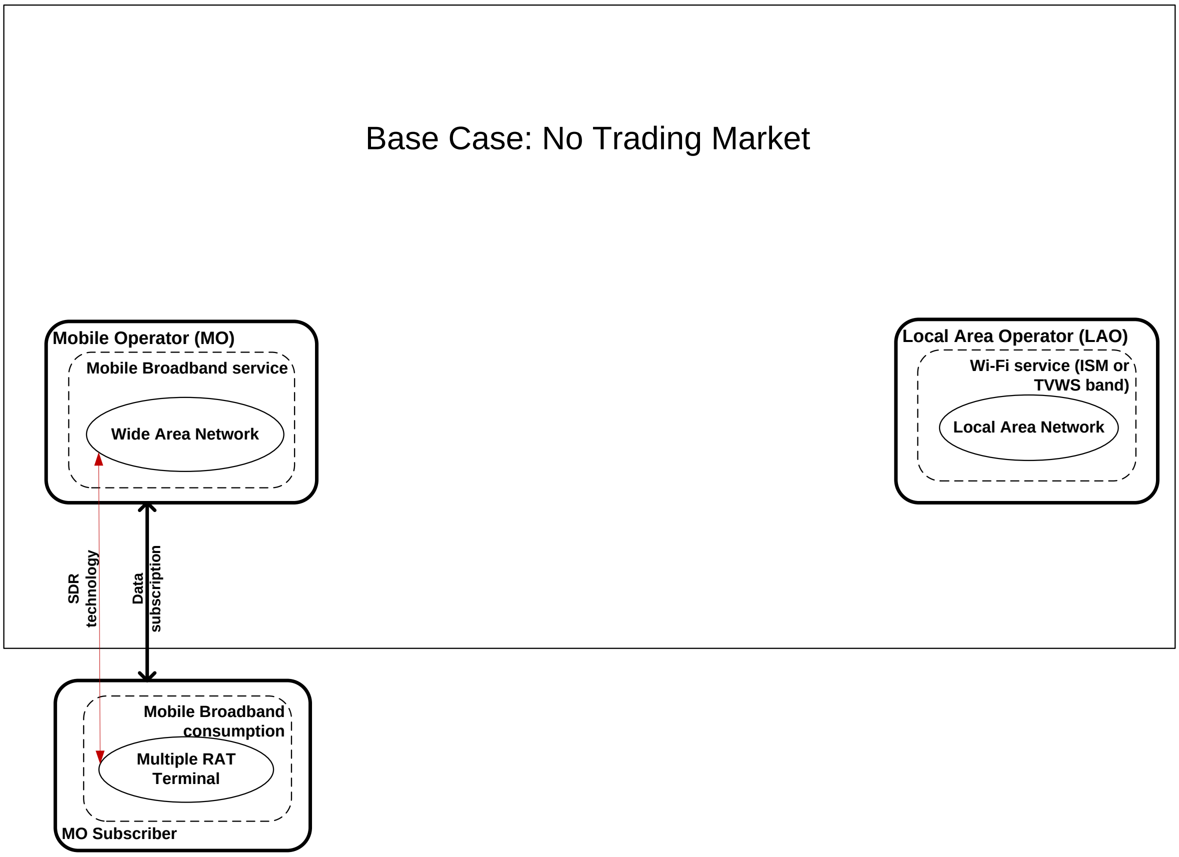

Figure 3-3 Part of value network design illustrating no trading market scenario

The MO subscriber's primary role is that of mobile broadband consumption and they are assumed to have frequency-agile radios which are able to switch to the assigned band and use the appropriate modulation and coding format. It would also require some kind of signalling overhead in between MO and its subscriber in order to notify which particular band to use.

Depending on the market scenario, LAOs either operate in ISM or in the TVWS band and correspondingly they require access points which are IEEE 802.11b/g and IEEE 802.11af standardized as part of their network infrastructure. The role of such LAOs could be taken over by commercial Wi-Fi operators, Wi-Fi hot spot providers and other companies offering Wi-Fi access, venue/facility owners etc.

MOs serve data demands of their subscribers primarily using their macro cellular-network infrastructure. The business interface between them is defined in terms of a data subscription agreement and on the technical level both of them possess the required CR technologies providing them the capability to participate in different market scenario. MOs experience network congestion if they do not have sufficient capacity to fulfill their subscriber's data demands and at the same time it is possible that there exist LAOs within same geographical region and with availability of excess unused capacity.

However as shown in Figure 3-3 there exists no facilitator which could provide MOs and LAOs a platform to interact and perform capacity trading. This situation clearly represents a scenario where a mismatch exists between demand and supply of data capacity as MOs and LAOs function independently.

3.1.2 Wi-Fi capacity market scenario description

Next we discuss the case of Wi-Fi capacity markets (Case1) which is built upon the scenario presented in the base case. In order to create a functioning trading market, it is required to have an intermediary for pooling the resources and matching the supply and demand sides of the equation. Hence we introduce a new market entity, i.e. a spectrum exchange (SpecEx) to facilitate the capacity trading. The structure of spectrum exchange is such that it acts as an information registry (spectrum database) of the amount of capacity available with different LAOs and their corresponding APs distributed over a geographical region. A capacity broker operates within a spectrum exchange with a role of matching the offers to lease extra capacity posted by the LAOs and offers to buy excess capacity posted by the MOs. With the introduction of spectrum exchange the market situation changes and is shown in following Figure 3-4.

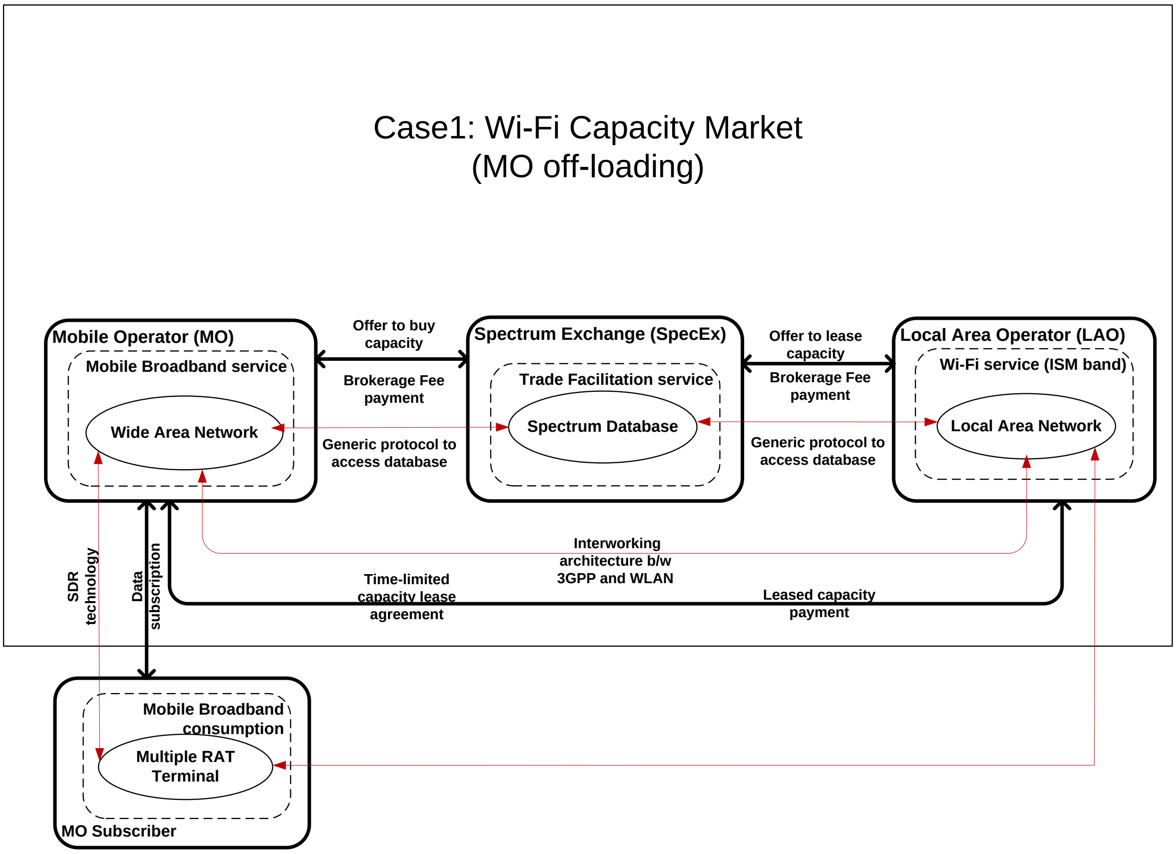

Figure 3-4 Part of value network design illustrating Wi-Fi capacity market scenario

The functioning of Wi-Fi capacity trade occurring in between MOs and LAOs facilitated by spectrum exchange is illustrated in the above figure where along the technical interface a generic protocol to access the spectrum database exists which is used by the MOs to query for availability of APs with excess capacity and is used by the LAOs to report the presence of their APs with available excess capacity. Then along the business interface the MOs post their offer to buy the amount of excess capacity and LAOs post their offers to lease extra capacity. A payment mechanism exists in between MOs, spectrum exchange and LAOs such that the trading and brokerage fee is received by the spectrum exchange.

Once a successful trade is completed MOs get temporal rights to use the leased capacity from LAOs until the new trading cycle begins. When the offers to buy and sell are matched in between MOs and LAOs, a time-limited capacity lease agreement is decided between them. Accordingly the flow of payment occurs from MOs to LAOs depending upon the amount of capacity which has been leased. At the technical interface an interworking architecture is used (as described in the literature review chapter) to offload the MO subscriber from their cellular-network infrastructure to local area network.

3.1.3 Super Wi-Fi capacity market scenario description

As an evolution of the previous case we discuss the super Wi-Fi capacity markets (Case2). Super Wi-Fi basically represents Wi-Fi kind of operation in TVWS which has also been referred to as the Wi-Fi 2.0, White-Fi and Wi-Fi on steroids. The market configuration consists of LAOs (having super Wi-Fi enabled APs), MOs, spectrum exchange and a new market entrant i.e. Television broadcasters (TVBs) as shown in following Figure 3-5.

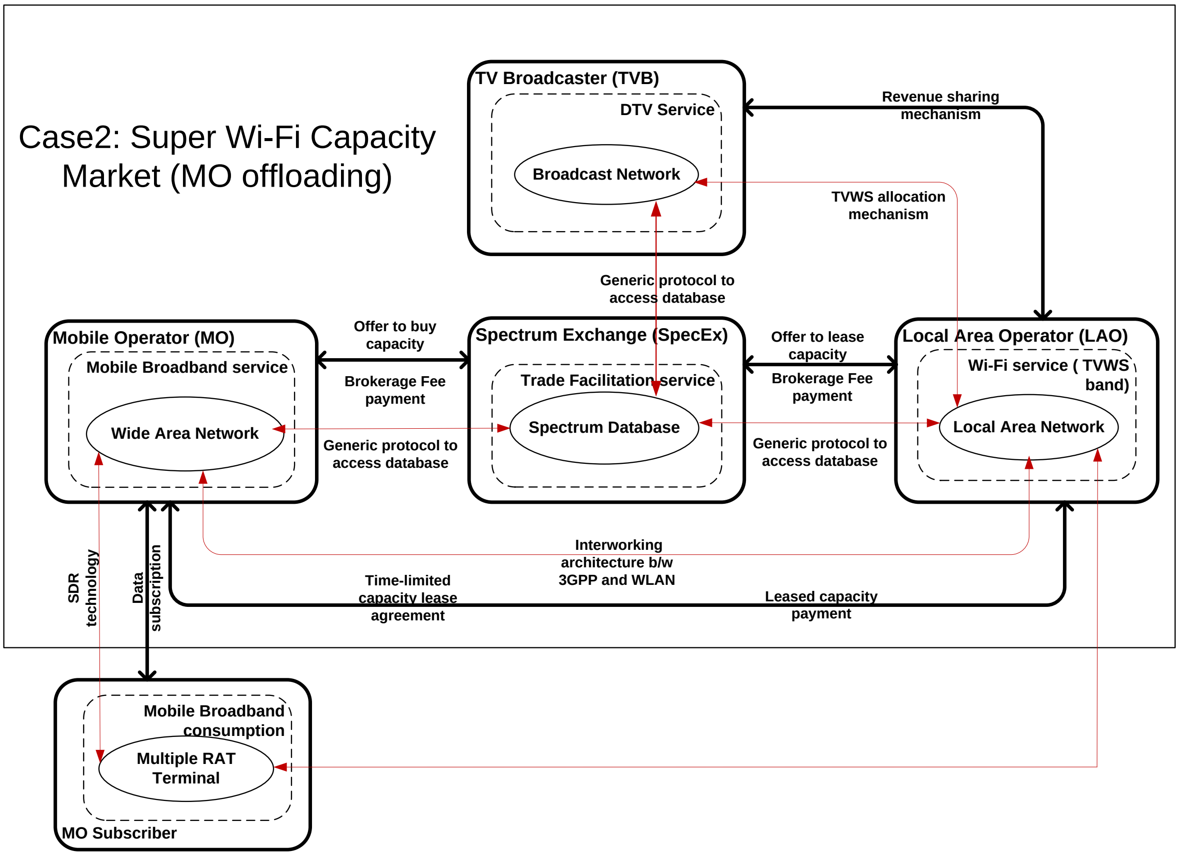

Figure 3-5 Part of value network design illustrating super Wi-Fi capacity market scenario

As when TVBs decide to participate in trading markets their primary task becomes protection of their transmissions from the interference which could be caused by the operation of secondary users. Thus the allocation of TV spectrum to LAO for Wi-Fi kind of operation is supported by a TV white space database which represents the required technical component.

We envision the realization of this case in the form of three-tier trading market. At the first stage there is an interaction between LAOs and TVBs facilitated by the spectrum database. LAOs identifies the available white spaces using the database and then accesses it as an unlicensed secondary white space device. A revenue sharing mechanism exists over the business interface in order to compensate TVBs for secondary usage of their licensed band and in some case even causing interference to their transmissions. It is important to note here that LAOs do not get an exclusive usage right of the white space, thus there is a possibility of multiple unlicensed secondary devices existing together.

At the next stage there is an offloading interaction between MOs and LAOs facilitated by spectrum exchange. This offloading interaction is similar to the one we discussed in previous sub-section and can be considered as spectrum subleasing where TVBs are acting as indirect supplier of capacity to MOs. As it can be seen in Figure 3-5, the features of technical and business interface are also same as what we discussed for the previous trade scenario.

Thus within this trading scenario TVBs make extra profits out of their otherwise unused portions of spectrum, LAOs gets an access to new spectrum for providing Wi-Fi kind of services to their subscribers and MOs gets the required capacity to ease its network congestion.

3.1.4 TVWS spectrum leasing market scenario description

Finally, we discuss the market based on spectrum leasing (Case3) which represents the last incremental step in our evolutionary approach. In this case primary user (i.e. TVBs) grants exclusive usage rights to a licensed secondary system (i.e. MOs) in TVWS for a pre-defined lease time through an auctioning process. A time limited spectrum lease agreement is decided upon in between the MO and TVB at the business interface and payment mechanism is in accordance with the price which is an outcome of auction. At the technical interface MOs require the CR capable base stations for accessing and using the TVWS band obtained through auction.

Market configuration consists of MOs, SpecEx and TVBs as shown in Figure 3-6. TVBs now replace LAOs as a direct supplier of spectrum to MOs. We model this scenario with spectrum exchange being a facilitator based on auctioning mechanism.

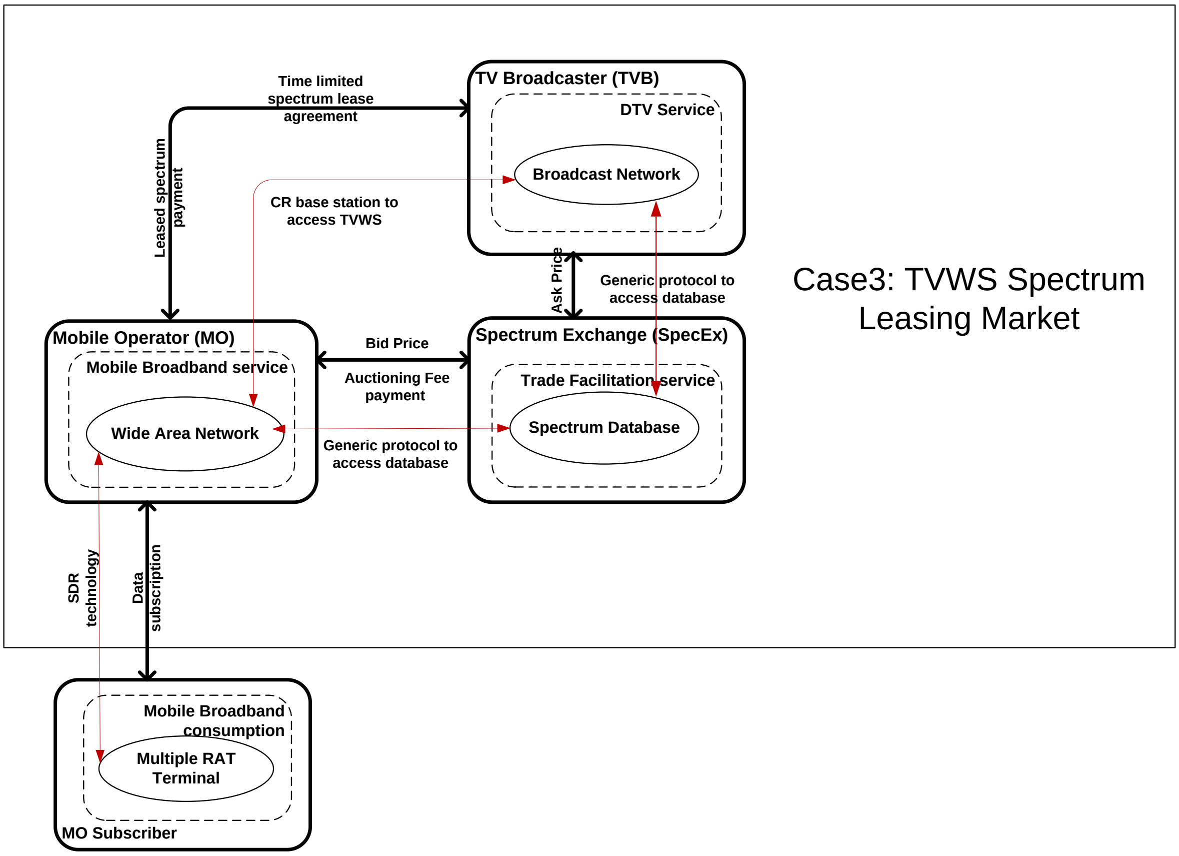

Figure 3-6 Part of value network design illustrating TVWS spectrum leasing market scenario

The functionality of this spectrum exchange is similar to the one discussed before with the only difference that it involves the role of auctioneer rather than a capacity broker. Auctioning facility is required since a contiguous band of TVWS is put up for auction where MOs post their bidding price depending upon their requirement for extra spectrum while TVBs post their ask price to auctioneer within SpecEx. Auctioneer then decides the winning MO who is given usage rights for utilizing the allotted band for a fixed duration as agreed over the length of lease time. Considering that MOs get an exclusive access to TVWS and do not expect interference from any other secondary system, they can offer a guaranteed QoS for their services which was not possible in the offloading scenario.

3.2 Agent based model of market mechanism

We use agent based modelling for evaluating the designed market mechanism. After having reviewed the tutorials on ABM and research work conducted on setting up and simulating the spectrum trading markets using ABM, we have identified it to be an efficient and resourceful tool for simulating different trading scenarios within our market mechanism. Next we give a short background introduction to ABM and further discuss how it has been used for setting up our model.

3.2.1 Background for Agent Based Modeling

ABM is a new approach towards modeling in which individuals and their interaction with each other and their environment are explicitly represented within a simulation tool used for the modeling purpose. This makes it possible to explore the connection between the micro-level behavior of individuals and the macro-level patterns that emerge from the interaction of many individuals. As mentioned before these individuals used for the modeling purpose are referred to as the agents who have their pre-defined behavior and capability to make independent decisions.

Macal & North (2010) in their tutorial for Agent Based Modeling and Simulation (ABMS) have listed down situations for which ABM can offer distinct advantages to the conventional simulation approaches and once it has been identified that the ABM is the correct modeling choice, Macal & North (2010) gives the general steps in building an agent model. These steps are described as followed:

- Step 1: one needs to identify the different type of agents (along with their attributes) which would be required to define the whole system.
- Step 2: the environment in which agents are going to live and interact with needs to be defined.
- Step 3: defining how the agent behavior going to evolve as a result of their interactions amongst each other and their interaction with the environment.
- Step 4: to define which agents are going to interact and under what conditions do they interact during the simulation.
- Step 5: after following all the above steps, the final step lies in simulating the model in the chosen ABM software environment.

ABM tools provides an edge over the traditional modeling and analysis tools and as a result it is now being used for modeling purposes in various fields such as in Biology (population dynamics, ecological networks etc.), Social Sciences, Economics (financial markets, trade networks) etc. ABMS has its roots in complex adaptive systems (CAS) where the system design principles are based on bottom-up approach in contrast to the top-down approach taken in case of, for example system dynamics another method used to model dynamic behavior. Moreover ABM provides the flexibility of working with large number of autonomous and heterogeneous agents which becomes a complex task to perform in other modeling methods such as in system dynamics. Next we introduce and compare some of the popularly used toolkits for building small scale ABM.

ABMS modeling toolkits

A number of free and open source multi-agent programmable modeling environment are available to use. Depending on the scale of system to be modeled different toolkits are available such as the *NetLogo*[10] developed at Northwestern's Center for Connected Learning and Computer-Based Modeling (CCL) and *REPAST (Recursive Porous Agent Simulation Toolkit) Simphony*[11] (North et al. (2007)) developed by the Argonne National Laboratory. Proprietary toolkit such as *AnyLogic*[12] is also available. For a small scale model (with number of agents extending to hundreds) desktop based ABMS tools are sufficient and could be designed on a workstation with ease, however in case of large scale models (with number of agents extending from thousands to millions) high performance computing clusters may be required. These software environments come with extensive documentation and tutorials. They are also equipped with models library, which is a large collection of pre-written simulations that can be used and modified.

For our simulation purpose we have used the latest release of Repast Simphony (2.0) which is a Java based modeling system. It provides an option of building the model either in ReLogo or in Java. ReLogo is an agent based modeling domain specific language (DSL) which has been written in Groovy programming language. The advantage of using ReLogo is that it comes in with a number of predefined primitives[13]. These primitives act as the building blocks which could then be put together while modeling the complete system. One gets the similar flexibility (in terms of available primitives) while developing the model in NetLogo as well; however we decided to go forward with Repast ReLogo as our choice of modeling tool primarily due to the following two reasons:

[10] http://ccl.northwestern.edu/netlogo
[11] http://repast.sourceforge.net
[12] http://www.xjtek.com/
[13] http://repast.sourceforge.net/docs/api/relogo/ReLogoPrimitives.html

- Considering that Repast Simphony ReLogo has an Eclipse based integrated development environment (IDE), it has a better user interface and is easier to work with as compared to NetLogo
- The most important reason being ability to develop more complex models with lot more functionalities using Java (the tool can seamlessly integrate Java and Groovy components, thus a project could start off as a small and simple model developed using ReLogo and later it could be extended into a large scale complex model using Java).

Thus in order to extend the scope and bring in more sophistication within the model, Repast represents a better choice as an ABM toolkit compared to NetLogo.

3.2.2 Classifying market actors as different type of agents

Our trading model comprises of heterogeneous market actors which we refer to as spectrum users (SUs) offering different wireless services in their respective spectrum bands. SUs include the mobile operators, local area operators and television broadcasters. LAOs are further classified as $LAO_{Wi\text{-}Fi}$ operating in ISM band using IEEE802.11b/g standardized access points and $LAO_{Wi\text{-}Fi2.0}$ operating in TVWS using IEEE802.11af standardized APs. All of the above described SUs represent the demand and supply side of trading market; however one also requires specific market entities to find an optimum match between demand and supply. Spectrum exchange takes on that role as a trading venue for executing trades. As discussed in the previous section, depending upon the trading scenario SpecEx can be based on brokerage mechanism (Case1 and Case2) or on auctioning mechanism (Case3).

We have broadly classified all the actors participating in our ST markets under three categories of agents – consumer agent (CA), supplier agent (SA) and facilitator agent (FA). As we mentioned before that our market mechanism is MO centric and the trading markets have been set-up in such a manner that it is always the MOs who assume the role of CA. This assignment of MO being CA can be confusing as MOs are the service providers and not the consumers themselves. However if we look it in terms of our model assumptions according to which MO subscribers are not modeled explicitly but their demand for data is reflected in terms of traffic demand within MO’s network then it seems logical to consider MO as CA.

The role of SA is to facilitate CA in meeting their subscriber's mobile data demands either through leasing their own excess capacity (the capacity left with a SA after having served their own subscribers) or through a lease of unutilized portions of their spectrum. Depending upon the different trading scenario, a SA could be $LAO_{Wi\text{-}Fi}$, $LAO_{Wi\text{-}Fi2.0}$, TVB (indirect) or TVB (direct). The role of FA is to match the demand and supply side; hence it includes SpecEx with either a brokerage or auctioning functionality.

Considering that Agent based modeling is characterized by objectives of its individual agents which fundamentally represent the agent behaviour, within our model each one of the above described market participant (i.e. SUs, SpecEx as broker, or SpecEx as auctioneer) are modeled as autonomous agents who have a pre-defined behavior.

Behavior of different agents

Next we discuss the behaviour of agents present in our market mechanism. The different interactions which we studied in Figure 3-2 are guided by these behaviours, analysis of which can provide insights into the characteristics of different trading scenarios.

I. **Consumer Agent:** behaviour is illustrated using the flow chart diagram shown in Figure 3-7. As discussed before, MOs act as consumer agents in our model with an objective to fulfil the mobile broadband demand of their subscribers and maximize their profits. Thus MOs determine the amount of traffic to be served using their traffic demand function and whether they can serve this traffic using their own network resources or not. If MOs are not able to serve this traffic demand, they are required to make decision regarding the type of trading scenario to participate in. Depending on this decision, it is determined which all other type of agents does MOs interact with, since different trading scenario involves the participation of different market players.

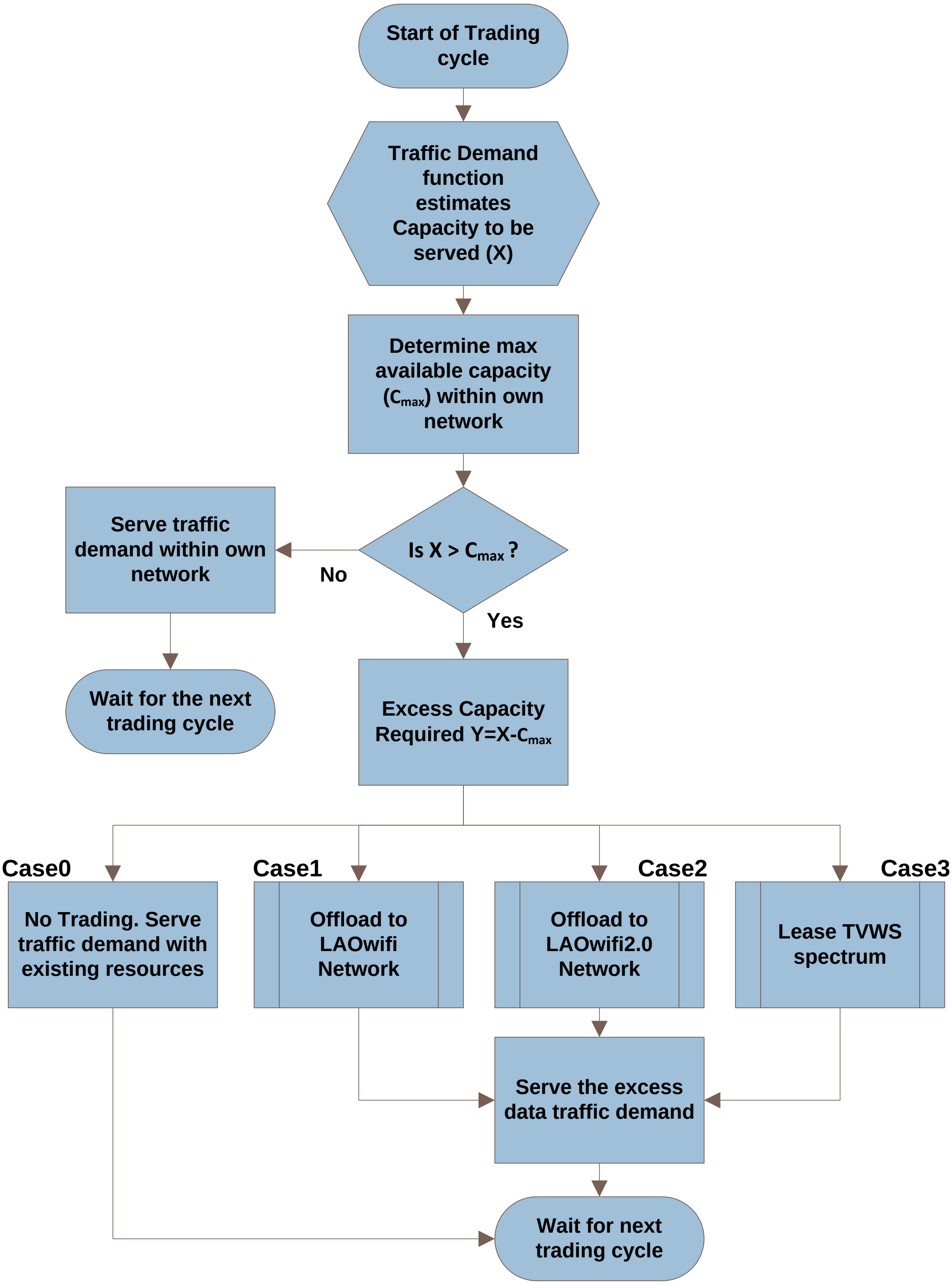

Figure 3-7 Flow chart representation of consumer agent behavior

If MOs take the offloading path, they post their requirement of excess capacity to the broker functioning within spectrum exchange as shown in Figure 3-8. The broker then matches the demand and assigns whatever excess capacity is available with the LAOs on a lease basis. Depending upon the capacity which is leased, MOs update their mean traffic demand function as part of the feedback mechanism implemented within the model and configure the network infrastructure required to make use of the leased capacity.

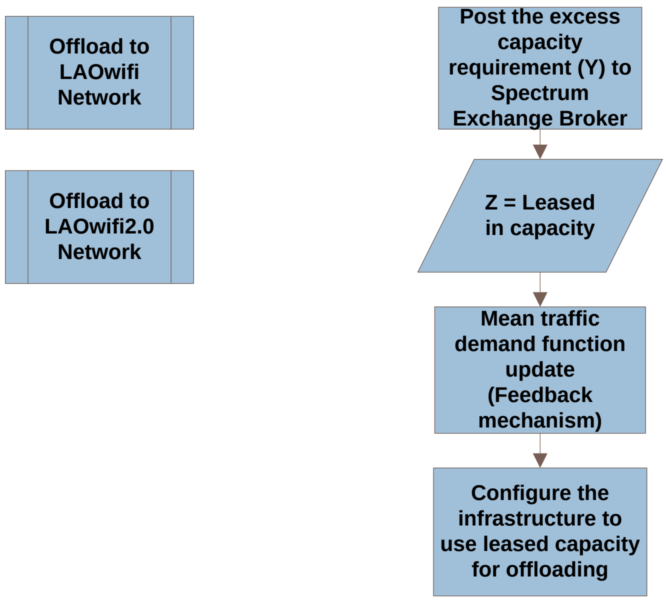

Figure 3-8 Flowchart representing CA behavior during offloading scenario

However in case of spectrum leasing scenario (Figure 3-9), MOs first calculate their bidding price using the zero-intelligence-plus (ZIP) bidding strategy (Cliff & Bruten (2007)) as explained in Appendix B. This bid price is then posted to the auctioneer functioning within the spectrum exchange based on which the winner is decided. The winning and losing MO adjusts its profit margin according to ZIP bidding strategy as a mark of their preparation for next bidding round. And the winning MO configures the network infrastructure required to make use of leased TVWS spectrum.

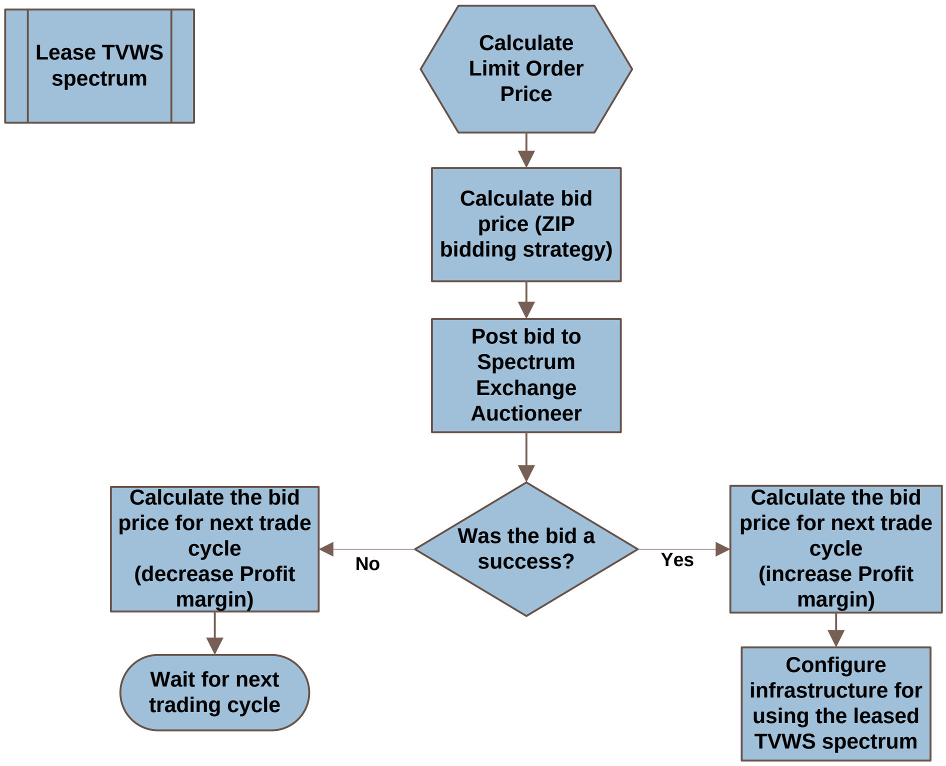

Figure 3-9 Flowchart representing CA behavior during spectrum leasing scenario

II. **Facilitator Agent:** objective is to provide a platform for execution of trade between CA and SA. As described before the SpecEx can have a functionality of a broker or an auctioneer depending upon the type of market. In case of the auctioning mechanism, bids are posted in the SpecEx where the auctioneer finds the winner amongst the bidders and allocates the TVWS spectrum.

However in case of brokerage mechanism, FA collects capacity demand requirements from CA and availability of capacity from SA. Then it follows a pre-defined procedure to match the buy and sell orders. This pre-defined procedure has been described in following flow chart diagram (Figure 3-10) for FA (i.e. broker here). According to this procedure broker maintains two lists for its operation – a demand (D) list (from the MOs) and a supply (S) list (from the LAOs). Using this list broker finds out the MO who has the maximum demand (D_{max}) for capacity and the LAO who has the maximum supply (S_{max}) of capacity available. It then tries to match the demand and supply according to following procedure.

If S_{max} is greater than D_{max} (implying that entire demand of the chosen MO can be fulfilled from excess capacity available with only one LAO), broker assigns the required capacity (equivalent to D_{max}) to the corresponding MO, updates its

D and S list and moves over to capacity demand of next MO. On the contrary if D_{max} is greater (implying that entire demand of the chosen MO cannot be fulfilled through excess capacity available with only one LAO and instead more number of LAOs would be required), broker assigns the capacity equivalent to S_{max} to the chosen MO, updates its demand and supply list and moves over to next LAO who can offer the required capacity. These operations are repeated until the maximum of either of supply or demand list becomes zero.

Once the matching of buy and sell orders are completed FA waits for the next trading cycle to be executed after the defined lease time. Figure 3-10 illustrates the FA behavior in case of spectrum exchange based on brokerage mechanism.

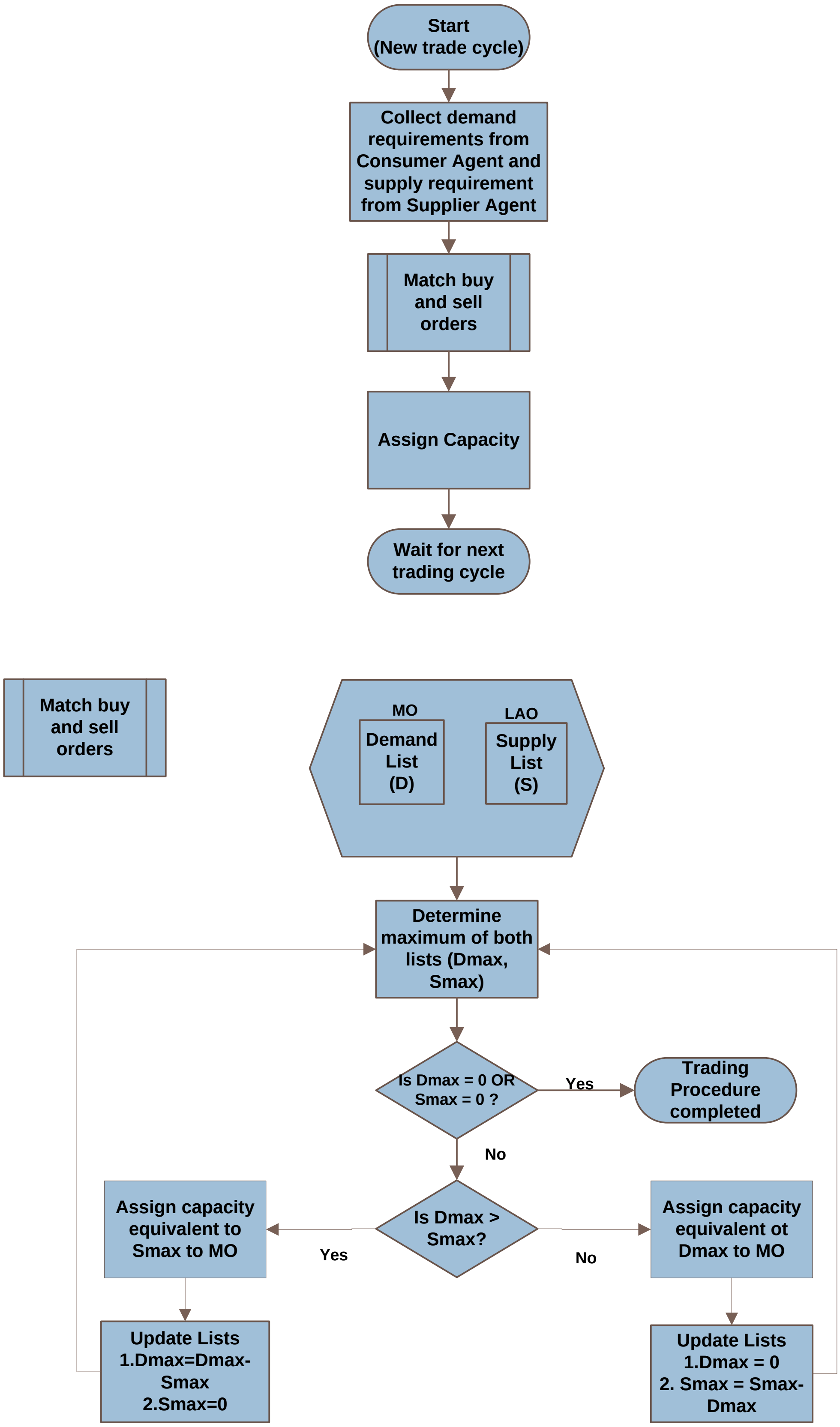

Figure 3-10 Flow chart representation of facilitator agent behavior with brokerage functionality

III. **Supplier Agent:** objective is to maximize profits from its un-utilized capacity or spectrum. SA links with the FA by posting their sell orders (of excess capacity) to the broker in case of capacity trading markets and posting their ask price (for the band of TVWS spectrum) in case of spectrum leasing markets. Therefore, SA participates in trading market whenever it has excess capacity or unused spectrum on offer.

3.3 Market assumptions and ABM configuration

This section describes the assumptions (within the ABM framework) which have been used for setting up the different market scenarios described through the value network design (Figure 3-2). The market mechanism design is built on the assumption that there exists the required technology for realizing the trading scenarios discussed before. The technology for deploying cognitive radio networks and DSA is assumed to have developed to a stage where it can be relied upon for facilitating secondary spectrum access.

For our analysis we model the aggregate traffic demand for each SU with an exponential distribution which is characterized by its mean and has been referred to as mean traffic demand (mtd) within the model. We also assume that the traffic demands faced by SUs are not correlated. One prime reason for this assumption being that within the ABM, one needs to model autonomous agents having their behaviour independent of any other agent. Thus any kind of correlation within traffic demand would violate that requirement of ABM.

We have also included a feedback mechanism for the mean traffic demand as experienced by consumer agent network (i.e. MOs). This feedback mechanism is used to model the MO’s subscriber behaviour of consuming more mobile data with fulfilment of their previous demands. This assumption find a close harmony with ideas put forward related to energy consumption and behavior by the economists Khazzoom and Brookes. According to Khazzoom-Brookes postulate (Saunders (1992)), increased energy efficiency tends to lead to increased energy consumption. And also within agent based model developed for Yoon et al. (2010), simulations have been performed with a similar kind of assumption where the demand for the spectrum resource increases with time according to Geometric Brownian Motion (GBM) – based stochastic process.

The parameters which we have assumed for representing the operating environment for MOs and LAOs are presented in the tables A-1 & A-3 (in Appendix A). All the assumptions made for designing different trading instances have been explained in detail within Appendix A. Here we present the important ones required to understand the simulation model.

Our trading model assumes its operation in a dense urban region with an area of approximately 1 square kilometer with a presence of three mobile operators and 900 access points uniformly distributed over the entire region. For our analysis we have assumed different configurations according to which these access points are shared amongst different LAOs. The configuration is represented in terms of – (number of LAOs) x (number of APs) and for our simulations it varies as (10x90), (30x30) and (90x10).

LAO's average spectral efficiency is assumed to be higher as compared to that of MO, since devices typically reside indoors and closer to the LAO access points than the MO base stations. Amongst two different kinds of LAO, $LAO_{Wi\text{-}Fi2.0}$ is assumed to have three times higher spectral efficiency as compared to $LAO_{Wi\text{-}Fi}$. An important thing to note here is that our trading market works as a non-real time market since the trade cycle take place at pre-defined time intervals. Thus the matching of demand and supply can't be executed at any time.

Next we discuss the revenue-cost model used for our simulations. It is important to break down and analyze all revenue and cost components involved in a trading scenario. Table A-4 (in Appendix A) lists all the values assumed for the revenue and cost components involved in capacity trading scenario. For a MO revenue earned per subscriber is assumed to be higher in offloading scenario as compared to the case where it gets an exclusive access to operate in TVWS. In spectrum leasing case, MO needs to deploy its own network infrastructure that results in higher CAPEX which is not required to a same extent during offloading scenario. Different cost components included in the model are – leasing cost (fixed component and usage based component), trade facilitation cost which include the transaction cost, brokerage cost and auction cost. The details of all this cost components have been provided in Appendix A.

During the auctioning process of TVWS channels, the cost of spectrum to MO depends upon the bid posted by it. We have adopted the zero-intelligence-plus (ZIP) bidding strategy for our simulations and the agents (CA and SA) make use of it for posting their bids in the market after they have decided on their limit order (LO) price (i.e. maximum price a buyer is willing to pay and minimum price a seller is willing to sell during an auction). We have assumed here that the mobile operator (i.e. CA) having larger subscriber base has higher willingness to pay for the spectrum and hence the LO prices are calculated accordingly. As a result the LO price for the MOs has following relationship –

$$(LO)_{MO1} > (LO)_{MO2} > (LO)_{MO3}$$

Limit order price for the TV broadcasters (i.e. SA) is a sensitivity analysis parameter and it is varied as –

$$(LO)_{TVB} < (LO)_{MO3}$$

$$(LO)_{MO3} < (LO)_{TVB} < (LO)_{MO2}$$

$$\text{and } (LO)_{MO2} < (LO)_{TVB} < (LO)_{MO1}$$

Analysis of Case3 is done over these three conditions and activity in a market starts with a series of mock auctions so that SUs can find an initial starting price for trading.

4. Simulation Results

In this chapter, we will demonstrate and evaluate the important features of our simulated agent based model. We will illustrate the results obtained by evaluating different trading scenarios and also analyze them to deduce some interesting observations. We discuss all these results with regards to the value network design of our market mechanism (Figure 3-2). The following Table 4-1 summarizes the cases which we are going to evaluate.

Table 4-1 Different trading market scenario

Case Scenario	Consumer Agent	Supplier Agent	Facilitator Agent
Base Case	MOs	None	None
Case 1	MOs	$LAO_{Wi\text{-}Fi}$	SpecEx on brokerage mechanism, Capacity Broker
Case 2	MOs	$LAO_{Wi\text{-}Fi2.0}$ TVB (indirect)	SpecEx on brokerage mechanism, Capacity Broker
Case 3	MOs	TVB (direct)	SpecEx on auctioning mechanism, Auctioneer

We evaluate the trading scenarios on two different fronts. One based on the traffic model (Table A-1 and A-3 in Appendix A) assumptions and other based on revenue and cost model assumptions (Table A-4 in Appendix A). The analysis based on traffic model gives an insight into the data volumes carried by different operators under different trading cases. Under this analysis we plot the total volume of traffic carried (in GB/day) on Y-axis and on X-axis we have different operators arranged in order of their popularity (i.e. larger the volume of traffic carried by operator's network, higher is its popularity).

The analysis based on revenue and cost model gives an insight into the performance of different market players which further gives an insight into an optimal range for the length of lease times. We define the performance of market players involved in different market scenario as followed:

Performance criteria over Wi-Fi and Super Wi-Fi capacity markets i.e. Case 1 and Case 2 –

- MOs = *[Revenue from offloaded subscribers] – [Costs incurred (leasing + brokerage + transaction)]*

- LAOs = *[Revenue from leasing capacity to MOs] – [Costs incurred (brokerage + transaction)]*
- SpecEx[14] = *Revenue from facilitating trade between MOs and LAOs*
- Capacity Broker[14] = *Revenue from providing brokerage facility to MOs and LAOs*
- TVBs[14] = *Revenue from sharing mechanism with LAOs*

Performance criteria over TVWS spectrum leasing scenario i.e. Case 3 –

- MOs = *[Revenue from subscribers served through leased TVWS spectrum] – [Costs incurred (leasing + auctioning + transaction)]*
- TVBs = *[Revenue from leasing TVWS spectrum to MOs] – [Costs incurred (auctioning + transaction)]*

Since we have the length of lease time as a sensitivity analysis parameter we evaluate the performance of all the market players over varying length of lease times. Such an analysis is useful in determining the optimum range of lease time for different trade scenarios, which we discuss it later in upcoming sections. As discussed in chapter 2, transaction costs associated with trading must be reasonable for spectrum trading markets to become practical since it is one of the key enabler for ensuring liquidity in the markets. Transaction costs primarily emerge in the process of searching for opportunities (capacity/spectrum to lease or buy) and thus have an explicit relationship with working model of brokers and spectrum exchange. However we look into some implicit relationships of transaction costs using our revenue and cost model such as its relation to LAO configuration, length of lease time and trading activity within the market.

The analysis using revenue-cost model (Table A-4 in appendix A) is performed according to following steps and is primarily used for finding the optimal length of trading cycle for different configurations and the best case scenario:

1. For each case (1 or 2), and correspondingly within each configuration we find the optimum lease time.

[14] Note: we have assumed cost overheads for SpecEx, brokers and TVBs to be small and thus have neglected it from the performance criteria of these actors.

2. Next we compare different configurations (within same case) across the optimum lease time obtained using Step1. This step helps in identifying the best configuration within each case.
3. Once the optimum lease time and the best configuration have been identified, we compare case1, case2 and case3 for finding the best case scenario in our model.

4.1 Base case – No trading scenario

A common feature which emerges out from our first analysis based on the volume of data traffic carried within the operator's network for different LAO configurations (10x90, 30x30, 90x10) is that it has a long tail shape (Anderson (2004)) where the MOs carry the bulk amount of traffic and the $LAO_{Wi\text{-}Fi}$ contributes to the tail. Figures illustrating the volume of data traffic carried by operators (under different LAO configuration) when they are arranged in order of their popularity are presented in Appendix C and we collectively refer these figures as *long-tail curves*. Here we present the result for 10x90 LAO configuration as shown in Figure 4-1.

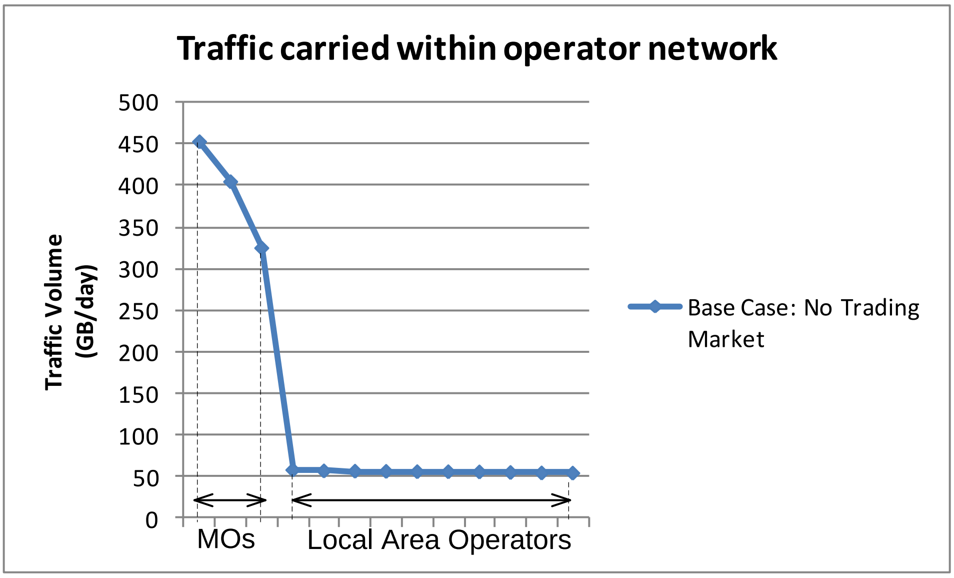

Figure 4-1 Long tail shape of traffic volume for operators when no trading market (10x90 LAO configuration)

These *long-tail curves* were expected and seem logical considering that we are comparing consolidated mobile data capacity represented by three MOs with fragmented Wi-Fi capacity represented by a number of LAOs spread over a geographical region. Hence this result also partly validates our model and the assumptions we have made for different parameters in setting it up.

The simulation result also brings forward a strong case for a Wi-Fi capacity trading market. As observed from the simulation results (illustrated in Figure 4-2), there exists a large amount of excess capacity available with Wi-Fi local area operators and at the same time MOs fall short to fulfill subscriber traffic demand. This represents a classic case of demand and supply mismatch. Figure 4-2 suggests that even though $LAO_{Wi\text{-}Fi}$ operators would not be able to completely fulfill the excess capacity demands of MOs; however they can be helpful in reducing congestion faced by MOs to some extent. Considering that it is expensive for the MOs to increase their existing network capacity, they can lease capacity from LAOs and offload some of its subscribers to LAO network during times of congestion.

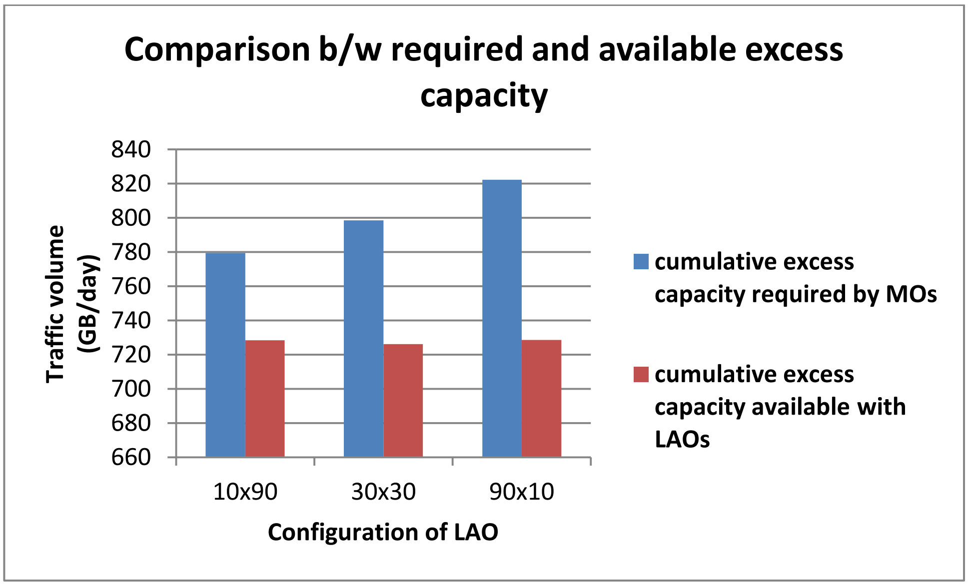

Figure 4-2 Mismatch between the demand and supply of capacity

4.2 Case1 – Wi-Fi capacity markets

Assuming that the Wi-Fi capacity trading markets have been deployed, on analyzing the total amount of traffic carried within the operator’s network when they are arranged in order of their popularity we observe that the tail of the *long-tail curves* rises as shown in Figure 4-3 for 10x90 LAO configuration.

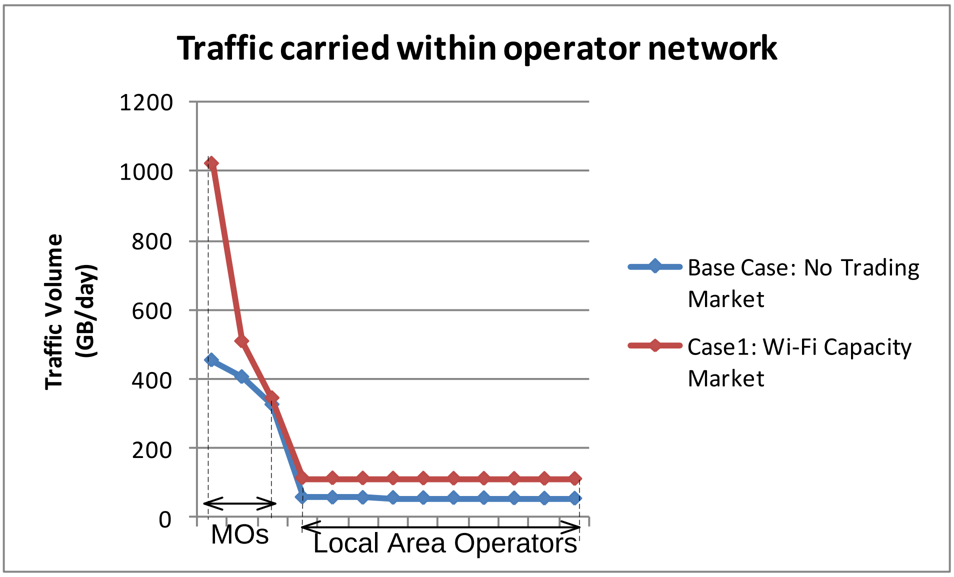

Figure 4-3 Long tail shape of traffic volume for operators when Wi-Fi capacity markets introduced (10x90 LAO configuration)

We observe this phenomenon since $LAO_{Wi\text{-}Fi}$ networks carry the offloaded data traffic of MOs as well. Another interesting observation is that the head of the *long-tail curves* also goes up for this scenario. This can be explained because of the feedback mechanism implemented within the model reflecting subscriber's behavior of consuming more mobile data once their initial demands are fulfilled. This increase in data requirement is partly met through MOs own network capacity (i.e. MO network utilization level increase) and partly through the offloading procedure.

We use the revenue-cost model (Table A-4 in Appendix A) to find an optimum range of lease time for different LAO configurations. The decision framework is based on the win-win scenario we aim to achieve for all the market players defined by high performance of MOs and LAOs, broker and SpecEx. Hence we analyze their performance over varying length of trading cycles (ranging from 500 to 10,000 seconds) and obtain the results as presented in Figure 4-4 for the case of 10x90 configuration and in Figure 4-5 for the case of 90x10 configuration. We observe that for lease times in range of 2000-4000 seconds cumulative performance of MOs and LAOs is better as compared to other length of lease times. If we compare the performance of the broker and spectrum exchange, then understandably it is higher for the smaller lease times (100-2000 seconds) which results in more number of transactions over a day and hence higher revenues. But since we are working within win-win framework, lease time in between 2000-4000 seconds would be a good choice for optimum length of trading cycle.

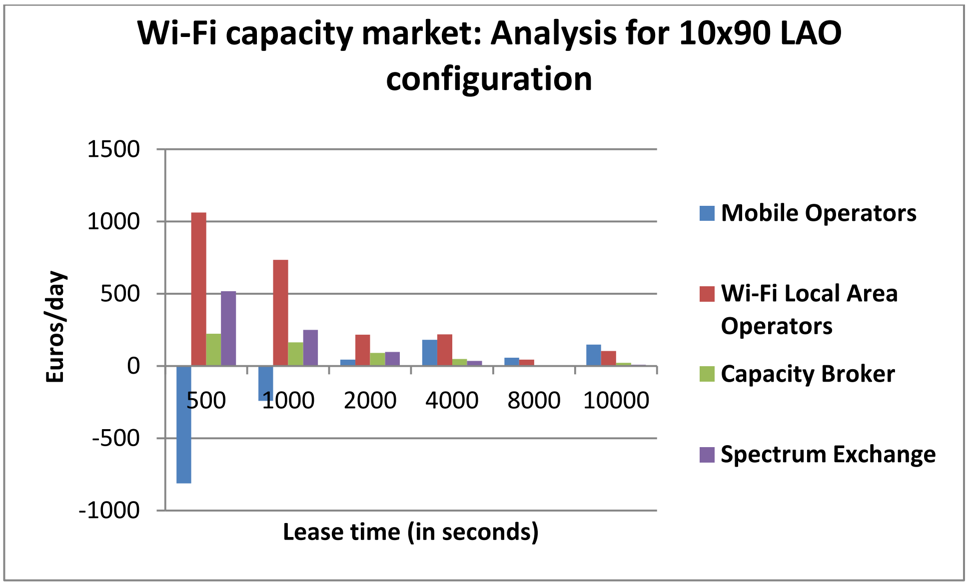

Figure 4-4 Case1: Performance of market players over varying length of lease time for a 10x90 LAO configuration

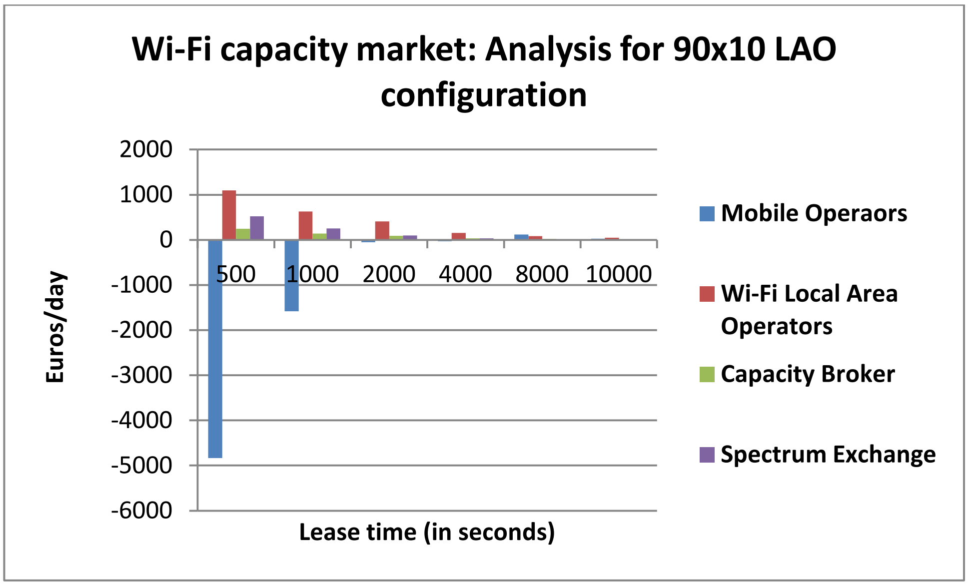

Figure 4-5 Case1: Performance of market players over varying length of lease time for a 10x90 LAO configuration

In order to better understand this behavior we further analyze how the transaction and brokerage costs (i.e. trade facilitation costs) vary with the different lease times and with different LAO configurations. The variation of transaction and brokerage costs with lease times is illustrated in Figure 4-6. We observe an interesting trade-off existing between trade facilitation costs, length of trading cycle and extent of trading activity in the market. With shorter lease times (100-500 seconds) the associated trade facilitation costs are so high for MOs that it negates all the advantage gained out of capacity trading. However in case of very long durations of lease times (8000-10000 seconds), these costs are very low but there isn't enough trading happening in the market which is not a favorable scenario for any of the agents. Thus it is required to find a middle ground which is favorable for all the market entities.

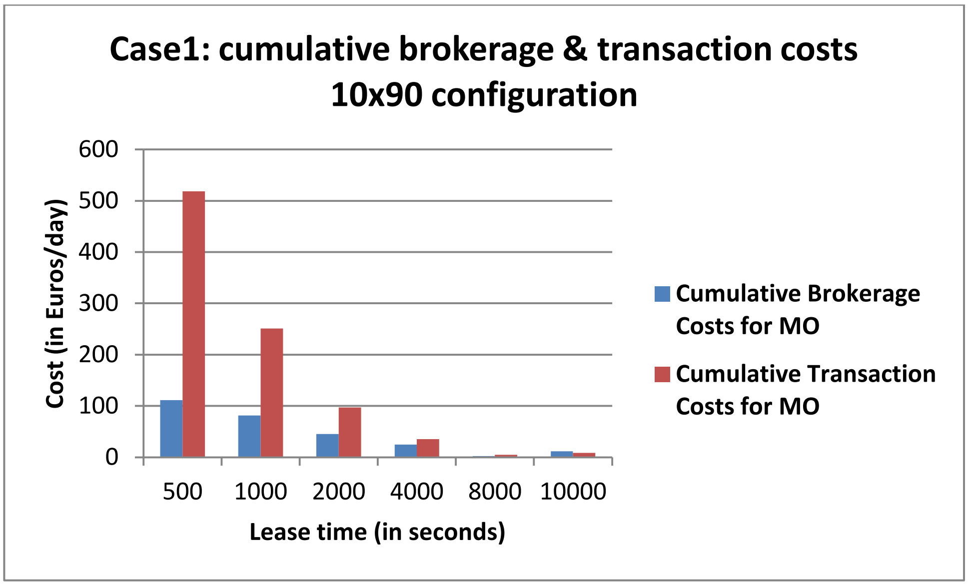

Figure 4-6 Case1: Variation of brokerage and transaction costs for MO with varying length of lease time

After concluding that there exists an optimal range for the length of lease time, we further compare different LAO configurations over this range. The details of the process behind this analysis have already been described before. Based on it we observe that MOs performs best in case of a centralized LAO configuration 10x90. The main reason for this could be attributed to the fewer transactions which are required for trading the same amount of capacity in a centralized LAO configuration as compared to the decentralized one (as shown in Figure 4-7). Moreover assuming that a MO lease same amount of capacity in both centralized LAO and decentralized LAO case, the cumulative usage based lease cost (being paid to LAOs) is going to be same in both the cases. However the fixed component of lease cost is going to vary. It is going to be much higher in decentralized case as the MO is required to deal with more number of LAOs and is required to pay each one of them the fixed component of the lease cost.

This observation supports the drawback put forward in Caicedo & Weiss (2007) regarding the adoption of distributed configuration as technical architecture for realizing spectrum trading. Caicedo & Weiss (2007) says that an architecture that supports distributed configuration might have higher transaction overhead and thus, possibly higher transaction costs for each trade configuration.

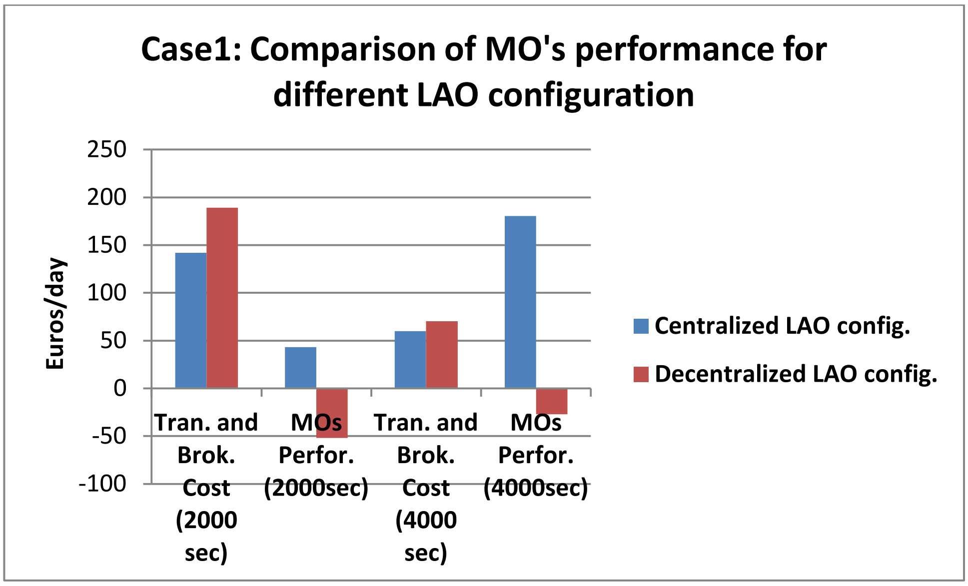

Figure 4-7 Comparison of MOs performance under centralized and decentralized LAO configuration (Case1)

Finally, as a result of the introduction of capacity trading mechanism, MOs excess capacity requirement is fulfilled to a great extent. However there are still instances where MOs are in need of more capacity which cannot be satisfied by $LAO_{Wi\text{-}Fi}$ operators. As it can be seen in Figure 4-2 the cumulative excess capacity required by MOs is higher as compared to the cumulative excess capacity available with LAOs, thus one needs to look beyond the Wi-Fi capacity markets. Moreover the mismatch between the demand and supply of capacity would get even worse once we take into consideration that the subscribers would consume even more data once their initial demands are fulfilled.

4.3 Case2 – Super Wi-Fi capacity markets

In order to counteract the above mentioned problem we introduce Super Wi-Fi capacity markets and analyze the simulation results to gauge its effectiveness in solving MO's network congestion issues. Similar to the previous cases we first analyze the total volume of traffic carried within the network of different operators when they are arranged in order of their popularity and as mentioned before we obtain a long-tail shape. However because of higher spectral efficiency on offer by super Wi-Fi which enables LAOs$_{\text{Wi-Fi2.0}}$ to fulfill all the extra capacity requirements, the tail further goes up as shown in Figure 4-8 for 10x90 LAO configuration.

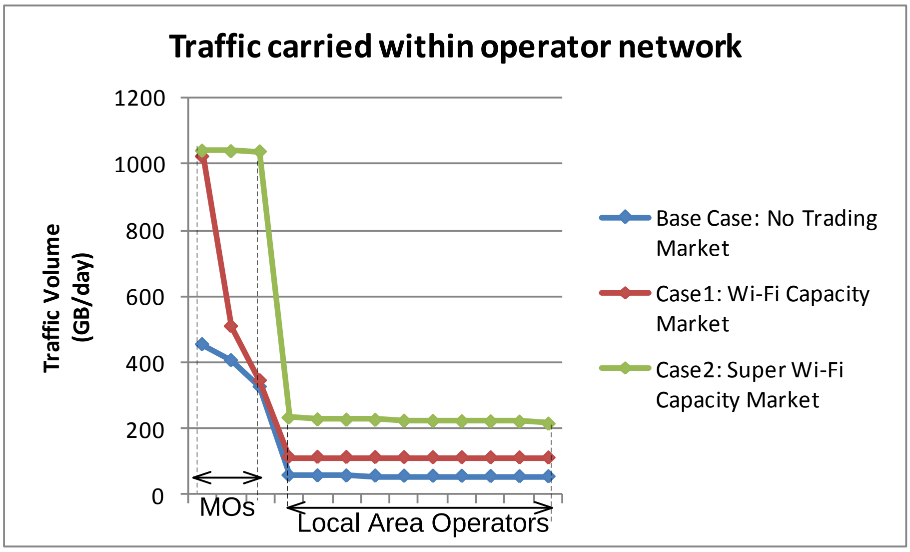

Figure 4-8 Long tail shape of traffic volume for operators when Super Wi-Fi capacity markets introduced (10x90 LAO configuration)

One interesting observation here relates to the traffic volume profile of the MOs constituting the head of these *long-tail curves*. Because of large amount of excess capacity on offer by Super Wi-Fi LAOs and the feedback mechanism for traffic demand implemented within our model, we observe that the head of the *long-tail curve* rises to such an extent that all the MOs now utilize their network capacity to maximum limits and approximately carry the same volume of traffic (Figure 4-8).

In order to find an optimal length of lease time for this case we perform an analysis similar to the one explained in previous section for the Wi-Fi capacity markets. The results are shown in Figure 4-9 for (10x90) configuration, in Figure 4-10 for (30x30) configuration and in Figure 4-11 for (90x10) configuration. Here again we observe that the lease time should be in the range of 2000-4000 seconds, for which all participating entities have high performance levels.

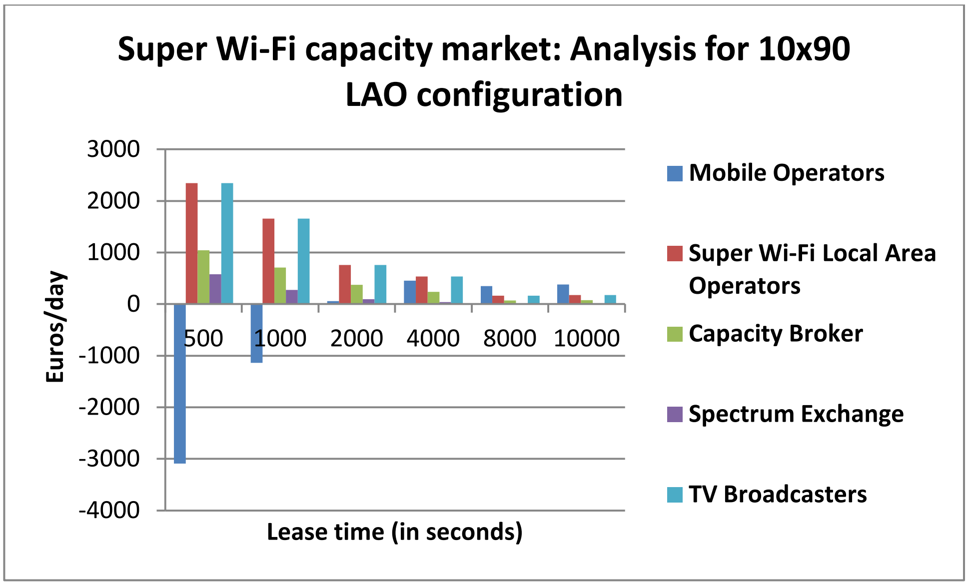

Figure 4-9 Case2: Performance of market players over varying length of lease time in case of 10x90 configuration

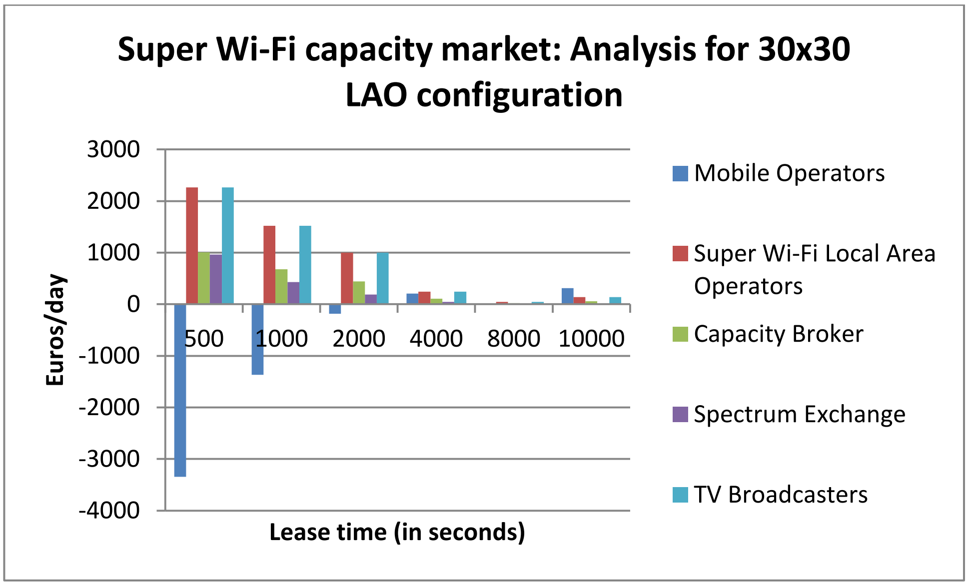

Figure 4-10 Case2: Performance of market players over varying length of lease time in case of 30x30 configuration

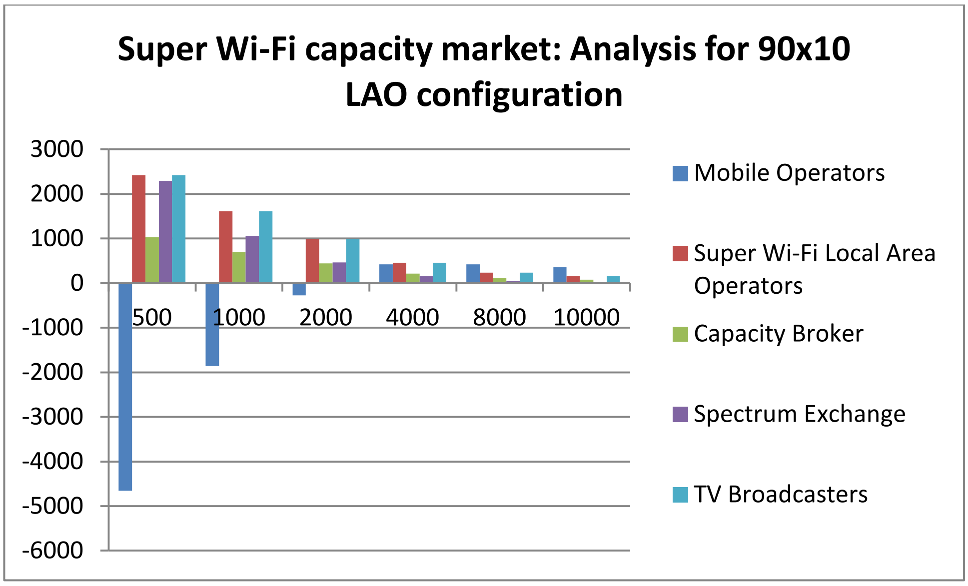

Figure 4-11 Case2: Performance of market players over varying length of lease time in case of 90x10 configuration

As our next step of analysis we identify the LAO configuration for which cumulative performance of MOs is better as compared to in other configurations. Here again the simulation results reaffirm the importance of adopting a centralized LAO configuration (i.e. 10x90) because of the involvement of low transaction and brokerage cost as compared to in decentralized scenario as shown in Figure 4-12.

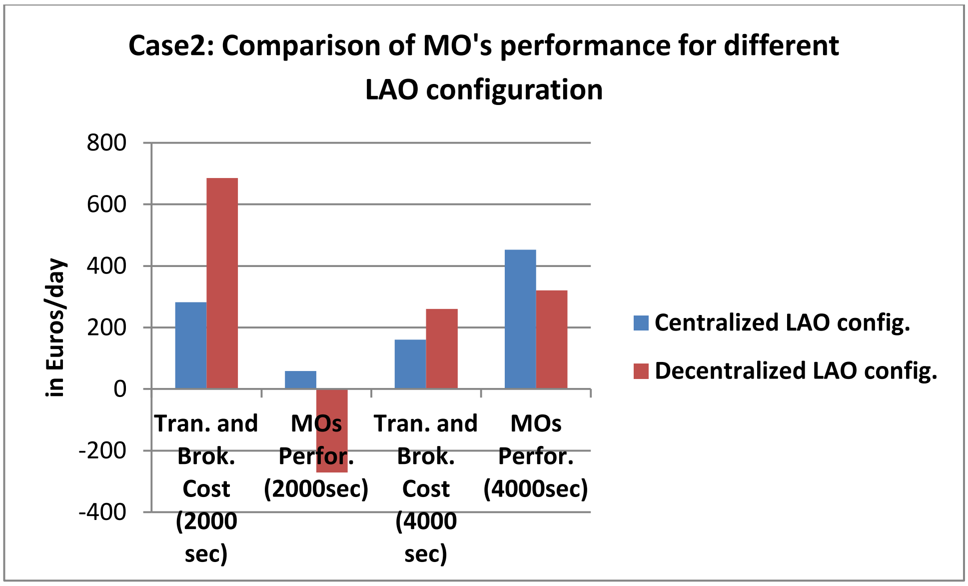

Figure 4-12 Comparison of MOs performance under centralized and decentralized LAO configuration (Case2)

We further analyze the brokerage and transaction cost variation with lease times, the results of which for 10x90 configuration is shown in Figure 4-13**.** If we compare the incurred brokerage costs for this case with the previous one then we observe that the brokerage costs are much higher here which could be attributed to higher volumes of capacity being traded and higher leasing cost assumed for this scenario. On a more generic level we observed the same trade-off happening between transaction and brokerage costs, length of trading cycle and extent of trading activity in the market which was visible for the Wi-Fi capacity trading markets as well.

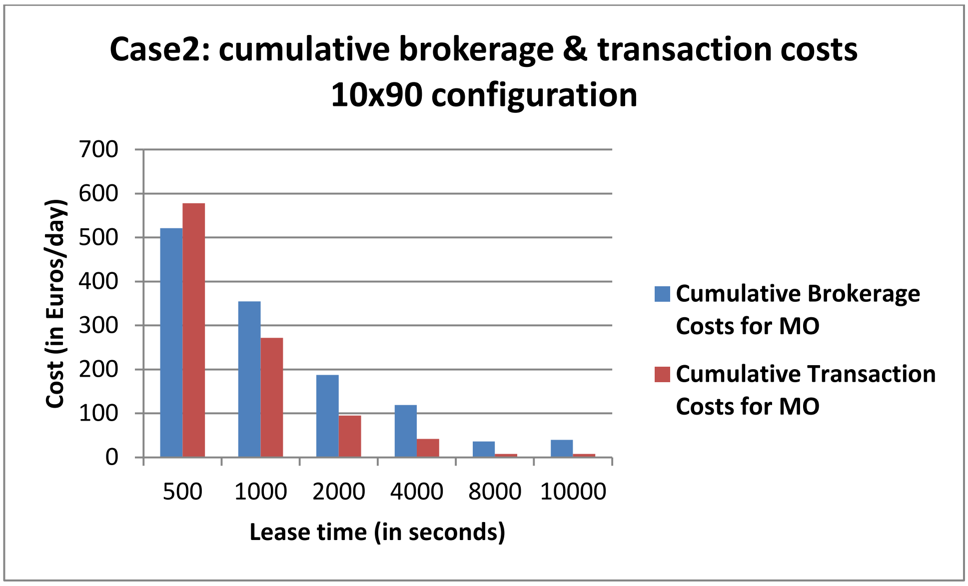

Figure 4-13 Case2: Variation of brokerage and transaction costs for MO with varying length of lease time

Another interesting observation we deduce from our simulation results is that the MOs requirement of excess capacity is completely fulfilled. $LAO_{Wi\text{-}Fi2.0}$ provides sufficient capacity to cater to the traffic demands of its own subscribers and that of MOs offloaded subscribers which could be observed from the simulation logs which shows that the excess capacity requirement of MOs is equal to zero after the introduction of Super Wi-Fi markets. This demonstrates the potential which Super Wi-Fi market holds in solving the issues pertaining to congestion in MO network.

4.3 Case3 – MO leasing TVWS band for exclusive usage

Finally, we analyse the simulation results for the TVWS spectrum leasing scenario where a contiguous band of TVWS is put up for auction and assigned to one of the MOs. For this case instead of iterating over different lengths of trading cycles, we make an assumption that TVWS band is leased out for a single day. This gives an opportunity to other MOs to bid higher during the next trading cycle and get an access to TVWS spectrum band.

Figure 4-14 shows how the traffic volume carried within operator's network when they are arranged in order of their popularity evolves as we take incremental steps towards the TVWS spectrum leasing markets. The MO winning the auction experiences a sharp increase in the volume of traffic carried within its network and it peaks up attaining a very high value. This phenomenon could be attributed to the fact that all the traffic now flows through MO's own network infrastructure deployed for accessing the leased spectrum which was not the case in capacity trading scenarios where the traffic flow was distributed in between MO's own network and LAO's network (for the offloaded subscribers). For the other MOs who were not successful in winning during that particular auction round, the traffic carried in their network is same as in the Base case, since we have not included the possibility of offloading to LAOs within this trading scenario. And as offloading doesn't happen thus the tail of the *long-tail curve* goes back to its initial state as observed for the base case.

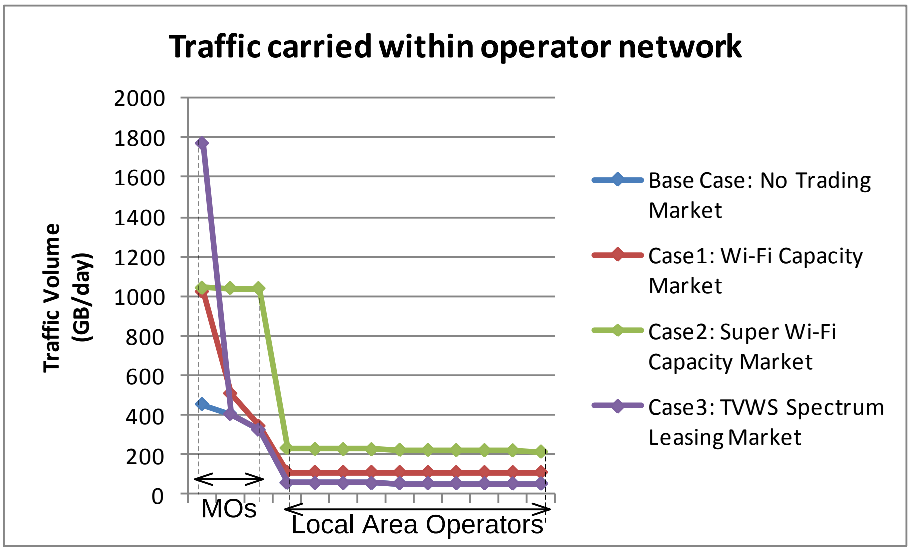

Figure 4-14 Long tail shape of traffic volume for operators when TVWS spectrum leasing markets introduced (10x90 LAO configuration)

As we analyze performance of different MOs and TV broadcasters for this case, we observe that only MO1 makes profit while for rest of the MOs leasing an entire band of TVWS is not a profitable venture. Considering that we have assumed MO1 to have a larger subscriber base, it has higher willingness to pay for the spectrum band and hence sets its limit order price higher than others. As a result of which MO1 wins the auction round more often than other MOs.

Finally we evaluate different trade scenario to identify a suitable strategy which could be adopted for the usage of TVWS spectrum. Super Wi-Fi capacity markets represent the local area strategy as the secondary users in this case are the LAOs while TVWS spectrum leasing markets represent wide area strategy with MOs being the secondary users for this case. We compare these trading scenarios studied as part of our evolutionary approach and weight the performance of MOs and TVBs against each other to identify which of the above two strategies perform better. As another performance metric we compare the aggregate volume of traffic served to the subscribers in each of the case with a notion that whichever trading scenario serves higher data volume might be more successful than other. Based on these comparisons we make our observation regarding the strategy which may offer more benefit for the usage of TVWS spectrum. The results of first comparison are shown in Figure 4-15 and for the second comparison in Figure 4-16.

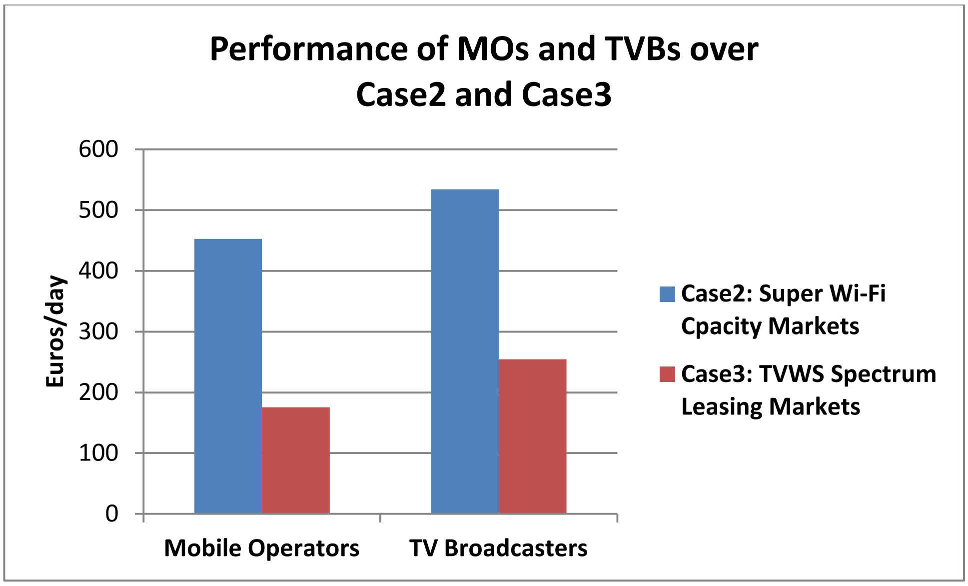

Figure 4-15 Comparison of MOs and TVBs performance over Super Wi-Fi capacity markets and TVWS spectrum leasing markets

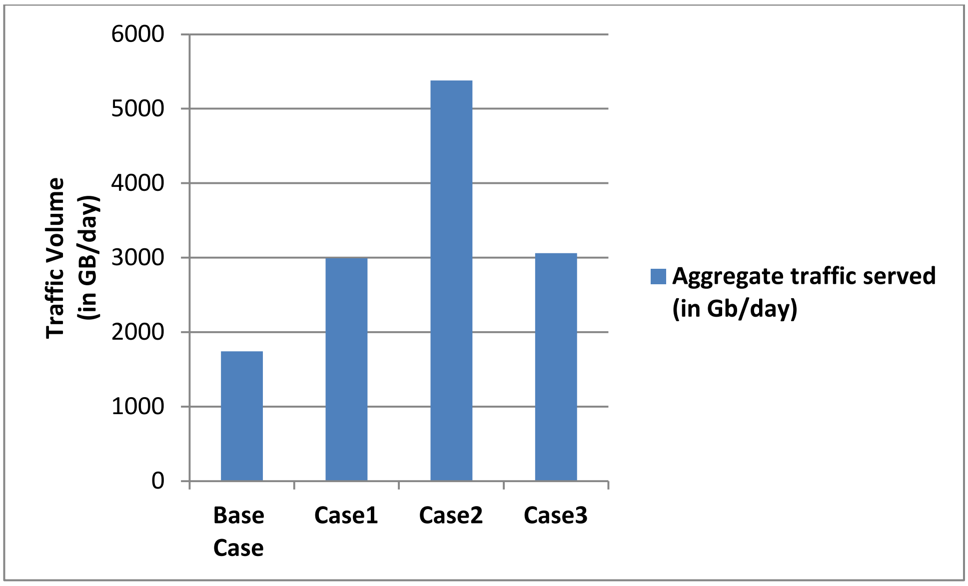

Figure 4-16 Comparison of different trading cases over the aggregate volume of data traffic served to subscribers

We observe from Figure 4-15 that both MOs and TVBs perform better in case of super Wi-Fi capacity markets. It is interesting to note here that TVWS spectrum leasing markets perform poorly even though we assumed the cost associated with auctioning and transaction process to be zero as described in Table A-4 (Appendix A). Even a comparison on the last performance metric i.e. the aggregate volume of traffic served in a day also brings out Case2 a clear winner as shown in Figure 4-16. Hence based on our evaluation of these simulation results local area strategy seems to offer more benefits for TVWS spectrum usage.

5. Conclusions

This chapter discusses the implications of results deduced from ABM simulations and also provides a summary of results. The directions in which the current work could be extended are also discussed later in this chapter.

5.1 Discussion

The existing centralized and traditional approach (i.e. command and control) towards the spectrum management has already been identified as the root cause for inefficient allocation of radio spectrum. This demands for a more decentralized and liberalized approach to be adopted by the regulators such that the spectrum could be accessed by the users in an optimized and efficient manner.Thus in this thesis we discussed different possible spectrum management framework for future wireless services and applications, ranging from unlicensed to opportunistic use to secondary spectrum trading. Each framework has its own advantages but also numerous challenges to overcome. It would be too early to identify one of these spectrum management models as a clear winner and project it as the chosen strategy moving into future. However since we argued for a scenario where all the market players benefit (i.e. a win-win situation) and are motivated to participate in realization of future spectrum management models; the secondary trading framework demonstrated by our market mechanism seems to have an edge with respect to potential market acceptance.

Spectrum trading is considered to be a market mechanism which would ensure maintaining economically optimal spectrum consumption. Realization of ST markets would depend on overcoming a number of challenges on technical front, but apart from that the spectrum liberalization policies adopted by regulatory bodies would also play an important role in making such market place a success. The regulators could be taken into confidence once a successful trading scenario is demonstrated in those spectrum bands which have minimal restrictions to use. Thus the evolutionary approach adopted in our market mechanism towards implementing ST markets is very logical. Accordingly the first easy and practical step could be a successful implementation of Wi-Fi capacity trading (in ISM band), follow it up by Super Wi-Fi capacity trading (in TVWS) and finally implementing the TVWS spectrum leasing markets.

As we evaluated these market scenarios using agent based modeling, some interesting observations were made regarding the behavior of different trading instances. Our simulation results demonstrated and provided support to the arguments being made in research literature that success of secondary markets depends a lot on achieving low transaction costs. Based on our simulation results we observed an interesting trade-off existing between the length of lease time, the costs involved for facilitating trade and the extent of trading activity in the market. A generic behavior observed during our analysis was that if lease time is too short then it results in very high transaction and brokerage costs while on the other hand for longer length of lease time there is not enough trading activity happening within the market which adversely affect the economic conditions of trade facilitators such as spectrum exchange and brokers.

Hence the time scale of spectrum trading turns out to be an important aspect for realizing an effective real-time trading regime. It poses technical and mechanism challenges associated with keeping transaction costs of frequent trading manageable. This observation implies that an optimal range for the length of lease time could exist for which the involved trade facilitation costs do not outweigh the economic advantages attained by the market entities participating in trading markets. Existences of such optimal range of trading cycles were demonstrated through our simulation results and even though the values obtained for optimal lease times are subject to vary with the assumptions made for setting up our model, on a high level it does reflect the importance of being aware of these optimal range as it might be required while designing the actual DSA system.

The assumptions we made regarding the traffic volume carried in operator’s network for different trading scenario find a close harmony with ideas put forward related to energy consumption and behaviour by the economists Khazzoom & Brookes according to which increased energy efficiency leads to increased energy consumption. A similar phenomenon is expected with mobile data consumption and our simulation results for the analysis of traffic carried within the operator’s network (the long-tail curves) for different LAO configurations demonstrates its occurrence.

Based on our simulation results, Super Wi-Fi capacity markets performed better as compared to other trading scenarios which we evaluated. These results have interesting implications for the kind of strategy which might be adopted for the allocation of

TVWS spectrum band. As per our observations it would be more beneficial to allocate TVWS for local area kind of operation rather than being allocated to wide area operators for their exclusive usage. To support the above argument if we compare spectral efficiency of these two kinds of operators we observe that local area operators have higher spectral efficiency as compared to the wide area operators for indoor locations where most of the traffic demand is likely to arise. Thus in that case trading markets based on local area strategy are more likely to be successful. However there also exists a possibility of adopting a strategy which involves the involvement of both wide area and local area operators, an optimal mix of some kind, such a scenario has not been simulated and forms the part of future research.

It is important to note here that because of a lack of prior empirical data available and uncertainties surrounding the structure, functioning and participants within ST markets, a number of assumptions had to be made when building our simulation model. The results which we have presented are subject to change with variations in the assumptions made for setting up the model.

5.2 Results summary

In this thesis we focussed on devising market mechanisms towards secondary usage of radio spectrum between heterogeneous set of market players. We were successful in demonstrating trading instances in between mobile operators, local area operators (Wi-Fi and Super Wi-Fi enabled), TV broadcasters and spectrum exchange (based on either brokerage or auctioning functionality) representing a set of heterogeneous actors. Using the value network design of our market mechanism we projected how the markets are going to evolve towards the secondary spectrum trading scenario. We further simulated and evaluated these trading markets to draw conclusions which are expected to provide inputs on technical, economical and regulatory front for institutionalizing ST markets as a tool of future spectrum management.

We summarize all the results by restating our research questions and inspecting how well were those questions answered. Our research was primarily driven by the following questions –

- *What is state of the art literature on secondary spectrum usage?*

    - *Which of the future spectrum management models being discussed in research literature fits in our objective of designing a 'win-win' market mechanism?*
- *What are the key features to design a practical and readily implementable market mechanism facilitating secondary spectrum trading?*
    - *What incremental steps will happen in the evolution process towards the secondary spectrum trading markets?*
- *Under which conditions and assumptions is the co-existence of multiple secondary users and systems within the proposed market mechanism economically favorable for all?*
    - *What impact does introduction of trading markets have on volume of traffic flowing through network of different operators?*
    - *What impact does the length of lease time have on realizing a successful ST market scenario?*
    - *Which of the two strategies – local area or wide area, is more probable to be adopted for usage of TVWS spectrum?*

To answer the first question we performed a literature review spanning over future spectrum management models, Wi-Fi offloading model, key enabling technologies for future spectrum management, TVWS spectrum opportunities and spectrum trading markets. We observed that much of the literature on the secondary spectrum use has been on developing technologies and system for opportunistic use representing the non-cooperative form of spectrum sharing and literature on cooperative secondary sharing is relatively sparse. However research carried out for the cooperative form of DSA is growing and is also seen to have numerous benefits over the non-cooperative DSA. In order to better understand the various spectrum management models being discussed in literature we classified those under three categories - license exempt model, non cooperative secondary usage model and market model based on cooperative secondary usage of spectrum.

We identified that market model based on cooperative secondary usage of spectrum fits in our objective of designing a *'win-win'* market mechanism and thus we adopted spectrum trading as underlying principle on which our market mechanism was designed. During the literature review we discussed a number of spectrum database architecture and deduced that spectrum database seems to be promising and pragmatic choice on technology front which would help in realizing a number of future spectrum management models. Thus we included spectrum database amongst the other technical components required for the functioning of our market mechanism.

To answer the second question we designed a value network configuration of the market mechanism using incremental approach. We proposed that the following incremental steps will happen in the evolution process towards the realization of secondary spectrum trading markets:

Step 1 Wi-Fi Capacity Market
Step 2 Super Wi-Fi Capacity Market
Step 3 Spectrum Leasing Market

The value network design of our market mechanism included different technical component, their role and corresponding actors undertaking those roles. Our design demonstrated the working of each of the above mentioned incremental steps and also illustrated the various interactions which are likely to occur between heterogeneous actors participating in different market scenario. We then simulated the designed market mechanism using ABM toolkit which simplified the process of modeling interaction between different actors because of a number of in-built primitives available with the toolkit.

In order to answer the final set of research questions we analyzed the results obtained from our ABM simulations. Here again ABM proved to be very resourceful in evaluating the performance of incremental and evolutionary steps towards secondary ST markets. Within the scope of assumptions used in setting up our ABM simulations we observed that traffic volume carried through different operator's network had a long tail shape where MOs carried the bulk amount of traffic constituting the head while LAOs carried only small volumes of traffic and constituted towards the tail portion. With introduction of different trading scenario the profile of head and tail of these *long-tail curves* varied as the volume of traffic carried within network of LAOs and MOs increased substantially. Hence introduction of ST markets resulted in higher utilization of available network resources.

Our analysis also showed that there exist optimal range for the length of lease time for which all the participating market players find themselves in economically favorable condition and thus meeting our objective of creating a *win-win* scenario. Given our modeling parameters this optimal length was observed to be in the range of 2000-4000 seconds over a day of capacity trading. Further when different LAO configurations were compared it was observed that the centralized LAO configuration performed better compared to the decentralized one. Variations in the brokerage, transaction and lease costs for different length of lease times and different LAO configurations largely attributed to the observation made above.

As a final step within our incremental approach, TVWS spectrum leasing markets were analyzed and compared with the capacity trading markets on the basis of -

- MO's and TVB's performance in the corresponding market over a day, and
- Aggregate volume of traffic carried by the all the operators within their network.

We observed that Super Wi-Fi capacity trading markets outperformed TVWS spectrum leasing market on both of the above chosen metrics. Based on evaluation of these simulation results we concluded that adopting a local area strategy for TVWS usage seems to bring in more benefits and could indirectly result in high performance level for MOs through adoption of capacity trading markets.

5.3 Suggestions for future research

Finally, we explore different directions in which the current research work could be extended. Here we discussed different trading scenarios which involved a strategy of giving an access to TVWS either to LAOs or to the MOs. For future work it would be interesting to study another scenario where both of these players have a significant role to play in TVWS usage. Thus in that case there can be an optimal manner in which the access to TVWS by LAOs and MOs could be defined which brings in better economic benefits to all the participating market entities such as the TVBs, MOs, and SpecEx etc. Such a scenario would be similar to mixed regime as discussed in Hwang & Yoon (2009). We can then have a Case4 including Super Wi-Fi operation and TVWS spectrum leasing.

Next if we shift our focus towards the existing agent based model built for this work, there is a possibility of bringing in a number of additional functionalities which could add value to the existing results and also give new insights in spectrum trading markets. As mentioned before, the current model does not factor in any challenges pertaining to interference management, DSA technology in use and quality of service. So as a next step, improvements could be brought about in the model by making it sensitive to the above mentioned challenges. The ABM toolkit (Repast Simphony) which we have chosen for simulation purpose provides a lot of scope for increasing the complexity of model as per the requirements. For example there is a possibility to include interference based pricing in our revenue-cost model, as currently no costs have been included within the model which would reflect the investments required on market player's part to deal with interference which might be caused during secondary usage of spectrum. Al Daoud et al. (2007) studied pricing in cooperative secondary sharing and showed that profits are improved when interference based pricing is used as compared to flat rate pricing scheme.

It would also be interesting to study how our proposed market mechanism could be deployed in the real world. This would require defining a number of processes for the relevant stakeholders and could act as guidelines for them to join the marketplace on a voluntary basis. The results from such an exercise could have implications for underlying technical architecture and possibly act as a roadmap for realizing secondary usage of radio spectrum based on cognitive radio technology.

Considering that TVWS spectrum is currently being targeted for the initial commercialization of DSA-based radio systems for secondary use, our market mechanism particularly focused on realizing successful trading in TVWS spectrum (as Super Wi-Fi capacity trading and TVWS spectrum leasing instances were simulated). However as seen in the literature review ST markets are visualized for other licensed bands as well. For example 2.6 GHz band has already been allotted in countries such as Finland, Sweden and Norway to MOs for deploying next generation LTE networks. However the MOs haven't put this band under desired usage and as a result it does not bring any economic value. This situation could change if a local area strategy as recommended by our simulation results for TVWS is also adopted for 2.6 GHz band and it is also brought under the ambit of ST markets. Thus we need to devise market mechanisms for other licensed frequency bands also and try to make our model as generic as possible.

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Appendix A: Description of assumption made for ABM model

Table A-1 Traffic model parameters of the operating environment (MO)

Parameter	**Description** *(value assumptions and comments)*
Geographical Area (A)	*Value = 1km^2* *Dense urban area*
# of MOs	*Value =3;* Represents a typical scenario prevalent in developed mobile markets
# of sector sites per km^2	*Value =1 (3-sector site);* *Cell radius of 1Km*
Bandwidth (BW) per MO	*Value = 20MHz;*
Average spectral efficiency	*Value = 1.67bps/Hz/sector;*
Max. Capacity per MO (C_{max})	*Value = 100Mbps;*
Total user population	*Value = 5000;* *Distributed as MO_1 = 2000, MO_2 = 1700, MO_3 = 1300*
Initial mean traffic demand per MO (mtd_i)	*Value = 50.56Mbps(MO_1) 42.98Mbps(MO_2) 32.87Mbps(MO_3);* Traffic demand is exponentially distributed
Total simulation time (T_{sim})	*Value = 86400 ticks (1 time tick = 1sec)*; Simulating trading over one day
Length of lease time (t_{lease})	*Varied as – 100,500,1000,2000,4000,8000,1000 time ticks* Sensitivity analysis parameter
Tradable entity	*Capacity lease in Mbps; Spectrum in MHz*
Mean traffic demand increment ($mtd_{incr.}$)	*Normally distributed (mean, std dev);* Mean= capacity leased during previous lease duration, std dev = 1
New mean traffic demand per MO (mtd_{new})	*Value = mtd_i + $mtd_{incr.}$ (feedback mechanism);* Updated after every trade cycle for each MO

Description of the assumptions presented in Table A-1:

We have assumed a dense geographical region with an area of 1km^2. The number of mobile operators is assumed to be three as it represents a typical scenario present in developed mobile markets. The assumptions regarding the number of sector sites per km^2, bandwidth per MO and average spectral efficiency per MO has been adopted from Markendahl et al. (2011) as shown in Table A-2.

Table A-2 Assumptions for spectral efficiency and cell capacity adopted from Markendahl et al. (2011)

Geotype	Cell radius (km)	Average Spect. eff.	Capacity of 3 sector site
Rural and Suburban	1 - 5 km	0,67 bps/Hz	20 Mbps (BW: 10 MHz)
Urban and Superurban	- 1 km	1,67 bps/Hz	100 Mbps (BW: 20 MHz)

The maximum user traffic which any MO can cater to has been assumed to be of 100Mbps and total MO subscriber population of 5000 has been assumed for an area of 1km^2 which represents a dense urban region and this user population is assumed to be divided amongst the operator MO1, MO2, andMO3 with a market share of 40%, 34% and 26% respectively. As mentioned before, the mean traffic demand is exponentially distributed and its value for each of the MO has been calculated based on the assumption that the average data consumption per month of each subscriber is 8GB.

Within the simulation toolkit that we have used (i.e. REPAST Symphony Relogo) the simulation time is represented in terms of ticks. We have assumed each tick to be equivalent to 1second (in real time) and thus for simulating a trading day, the simulation is run for 86400 ticks. The tradable entity in case of capacity trading markets (Wi-Fi and Super Wi-Fi) is measured in terms of Mbps and in case of spectrum leasing markets is measured in terms of MHz.

In order to incorporate a feedback mechanism within the mean traffic demand of MOs, we introduce another variable ‘mtd_{incr}’ whose value is assumed to be normally distributed with its mean being equal to capacity leased during the previous lease duration. Accordingly the new value of ‘mtd’ is determined as the sum of ‘$mtd_{initial}$’ and ‘mtd_{incr}’. An important thing to note here is that the value of the mean traffic demand does not increase indefinitely for the MOs. We have introduced an upper threshold for each of the operator which determines how much the ‘mtd’ can rise up to. The threshold value for each of the operator is given by: mtd_{max} MO1 = 250Mbps, mtd_{max} MO2 =

208Mbps, and mtd_{max} MO3 = 160Mbps. Then as a sensitivity analysis parameter we have the length of lease time varying according to the values as shown in the table A-1.

Table A-3 Traffic model parameters of the operating environment (LAO)

Parameter	**Description** *(value assumptions and comments)*
Wireless standard	*$LAO_{Wi\text{-}Fi}$ = IEEE802.11b/g, $LAO_{Wi\text{-}Fi2.0}$ = IEEE802.11af*
Total # of access points (APs)	*Value = 900;* Represents a typical scenario prevalent in dense urban area
Configuration	*Value = 10x90, 30x30, 90x10;* Represented as (# of LAO)x (# of APs)
Frequency band of operation	*$LAO_{Wi\text{-}Fi}$ = ISM & $LAO_{Wi\text{-}Fi2.0}$ = TVWS;* TVWS quantification ~ 22MHz in contiguous fashion and ~96MHz in non-contiguous fashion
Spectral efficiency	*Value: $LAO_{Wi\text{-}Fi}$ =2.7bps/Hz & $LAO_{Wi\text{-}Fi2.0}$ = 8.0bps/Hz*
Max capacity per LAO (C_{max})	*Values (in Mbps): $LAO_{Wi\text{-}Fi}$ = 12.15(10x90),4.05(30x30),1.35(90x10)* *$LAO_{Wi\text{-}Fi2.0}$ = 60(10x90),20(30x30),6.67(90x10)*
Mean traffic demand per LAO (mtd)	*Mean value: @(50% of C_{max}) for each scenario* Exponentially distributed and no feedback mechanism here

Description of assumptions presented in Table A-3:

Total number of APs are assumed to be 900 which represent a typical value prevalent in dense urban region with an area of 1 square kilometer. The value of spectral efficiency in case of LA operation within ISM band has been assumed to be 2.7bps/Hz. Since the standardization of Super Wi-Fi (IEEE 802.11af) is still under process thus spectral efficiency for this scenario is not exactly known and we have assumed it to be approximately 8bps/Hz. According to our assumptions the spectral efficiency of LA operators is higher than that of WA operators. As observed from Figure A-1, spectral efficiency of WA operator is highest near the base station but it decreases exponentially as we move away from it towards the cell edges. Now if we consider inside locations where most of the data demand is likely to arise, spectral efficiency of WA operator is expected to be even lower as compared to that of LA operators and hence it validates the assumption made above.

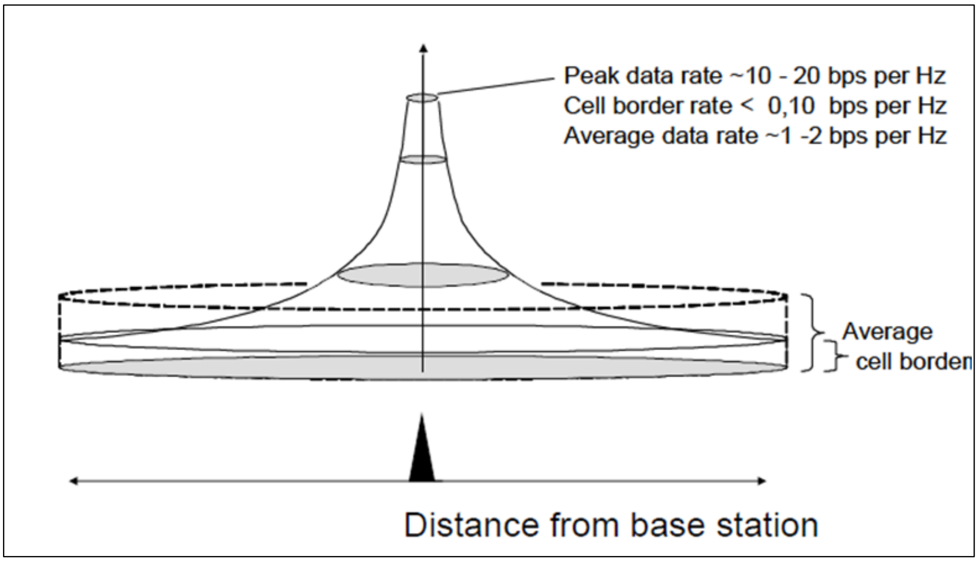

Figure A-1 Decrease in spectral efficiency of cellular systems with increasing distance from base station as illustrated in Markendahl et al. (2011)

Table A-4 Revenue and Cost model parameters of the operating environment

Reveue Model for MO			
Parameter	**Description** *(value assumptions and comments)*		
Revenue earned per Mb (rev/Mb)	*Offloading scenario (Supplier agent: LAO_{Wi-Fi}/$LAO_{Wi-Fi2.0}$)*	*Leasing TVWS spectrum scenario (Supplier agent:TVB)*	
	0.00026 Euros/Mb no network cost required for MO	*0.00013 Euros/Mb network cost required for MO*	
Cost Model for MO ***(in offloading scenario)***			
Parameter	**Description** *(value assumptions and comments)*		
Usage based leasing cost (lc)	*Supplier Agent: LAO_{Wi-Fi} 0.00005 Euros/Mb*	*Supplier Agent:$LAO_{Wi-Fi2.0}$ 0.000075 Euros/Mb*	
Fixed leasing cost	*lease/allocation time (in sec.)*	*Fixed cost (in Euros)*	
		LAO_{Wi-Fi}	*$LAO_{Wi-Fi2.0}$*
	100	*4*	*6*
	500	*6*	*9*
	1000	*8.4*	*12.6*
	2000	*10.92*	*16.38*
	4000	*13.1*	*19.66*
	8000	*14.41*	*21.62*
	10000	*15*	*22.50*
Brokerage cost (bc)	*@10% of the total leasing (fixed+usage based) cost (as Broker commision for matching capacity demand and supply)*		
Transaction cost (tc) (cost per transaction)	*0.5 Euros/transaction In between SpecEx & MO*	*0.5 Euros/transaction In between SpecEx & LAO*	
	(to be paid to the Spetrum Exchange(SpecEx) for facilitating trade)		
Cost Model for MO ***(in leasing TVWS spectrum scenario)***			
Limit Order price	*Calculated by each of the MO depending on their willingness to lease TVWS spectrum*		
Transaction and auction cost	*Zero; in order to compare across different trading scenario*		

Description of assumptions presented in Table A-4:

For a MO the prime revenue stream is through the services which it offers to its subscribers. We focus on the revenue from the mobile broadband services and measure it in terms of revenue earned per Mb (rev/Mb). The value (rev/Mb) assumed depends upon the scenario in consideration. For the offloading cases the CAPEX (capital expenditure) cost involved in producing a megabit of data is minimal as compared to the case of leasing exclusive spectrum band which requires high investments to be made in network infrastructure. Thus rev/Mb achieved in former case is higher as compared to the latter. These values have been adopted from an analysis done by McKinsey (2010). Following Figure A-2 (from the McKinsey (2010) report) projects the expected revenue and network costs to MOs for providing mobile broadband in future. Using the values projected in Figure A-2 we have assumed revenue to be equivalent to 0.3 US cents per MB which amounts to 0.026 Euro cents per Mb. The network costs have been assumed as 0.15 US cents per MB which amounts to 0.013 Euro cents per Mb.

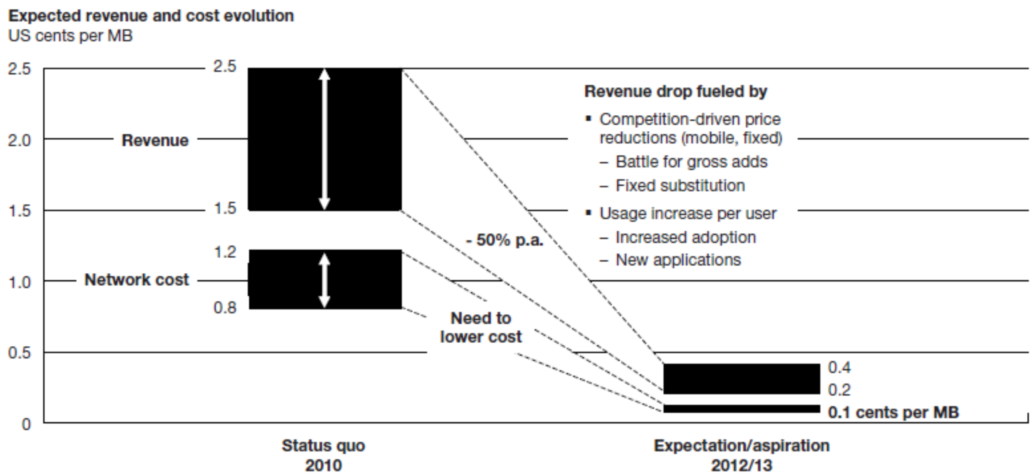

Figure A-2 Expected revenue and network cost evaluation per MB of mobile broadband data for the MOs as illustrated in McKinsey (2010)

We have assumed a variable cost structure incurred by the market participants. The various components of this cost structure are as followed:

I. Usage based lease cost – This component represents the flow of money from the MOs to the LAOs in lieu of the capacity being provided by them through their network of APs deployed within the concerned geographical region. This cost has been assumed to be 0.0005 Euros/Mb in case of $LAO_{Wi\text{-}Fi}$ and 0.00075/Mb in case of $LAO_{Wi\text{-}Fi2.0}$. The costs are higher because of better performance expected from super Wi-Fi in terms of better range and penetration of signals. The LAOs in super Wi-Fi case further shares it with the TV broadcasters in lieu of their usage of TVWS. Hence a revenue sharing mechanism (on percentage basis) is implemented between LAOs and TVBs.

II. Fixed lease cost – This cost component is again required to be paid by MOs to the LAOs depending upon the length of trading cycle (the values assumed are shown in the table). It is independent of the amount of mobile data consumed by the MO's subscriber over the LAO network. This cost is for safe guarding the LAOs against a scenario where the MOs lease excess capacity from them and do not make use of it during a trade cycle. In such a case, if only usage based cost is involved then the LAOs would not be able to extract any economic value out of their unused excess capacity. The LAOs in super Wi-Fi case further shares it with the TV broadcasters in lieu of their usage of TVWS. Hence a revenue sharing mechanism (on percentage basis) is implemented between LAOs and TVBs.

III. Brokerage cost – This cost component arises during the case when we are dealing with spectrum exchange based on brokerage facility and it represents the broker's commission of matching demand and supply. We have assumed this cost to be 10% of the total leasing cost (fixed plus the usage based component) and which is required to be paid by the MOs to the spectrum brokers.

IV. Transaction cost – Since spectrum exchange provides all the facilities and a central place over which the trade can take place, thus it is required to be compensated as well. Thus we have incorporated a transaction cost which is incurred by MOs and the LAOs and is given to the spectrum exchange. This cost has been assumed to be 0.5 Euros/transaction.

V. Auction cost – This cost component arises when we are dealing with spectrum exchange with auctioning facility (i.e. in Case3 – TVWS spectrum leasing markets) and is required to be paid by the MOs to the auctioneers present within the spectrum exchange. We have assumed this cost to be zero so as to bring a comparison in between different trading scenario. As shown through our evaluation results, Case3 performs poorly (in terms of MOs profits) compared to other trading scenario even though we assumed auction cost to be zero.

It is important to note that since there isn't enough empirical data which exist for ST markets, a number of assumptions were required to be made while deciding over the traffic model and revenue-cost model parameters. Thus all the simulation results are subject to variations in the assumptions which have been made and explained in this section for setting up the model.

Appendix B: Zero-Intelligence-Plus bidding strategy

ZIP bidding strategy has been adopted for the auction process in TVWS spectrum leasing scenario. MOs and TVBs use this strategy for posting their bid and ask price respectively in the market after they have decided on their limit order price (L), i.e. maximum price a buyer is willing to pay and minimum price a seller is willing to sell during an auction. We have adopted the use of this strategy from the previous work done in Caicedo (2009) on the simulation of ST markets. According to Caicedo (2009), this strategy is not computationally intensive and can be used to implement software based traders (agents) which can have their performance similar to human traders.

Here we discuss the fine details involved in the working of ZIP bidding strategy pertaining to our market model used in Case3. During any round of auctioning process trader agents (i.e. MOs and TVBs) are required to submit their bid/ask or the shout price. This shout price is dependent upon limit order price and the profit margin (μ) of trader agents. Profit margin determines the difference between the agent's limit price and the shout price. It varies in each auction round depending on the value of the last shout price and results of the previous auctioning process (i.e. whether the last shout resulted in a successful transaction or not).

Process from the buyer agent (i.e. MOs): Based on their requirements for excess capacity MOs post their bids during each round of auction. Assuming that transaction happens, the MO which wins that auction round increases its profit margin for the next round while the remaining MOs decrease their profit margins in order to improve their chances of winning the next round of auction. However in a case when no transaction happens, i.e. none of the MO's shout price is able to match with that of the shout price (ask) of TVBs, then all the MOs decrease their profit margins.

Process from the supplier agent (i.e. TVBs): For every successful transaction during a round of auction, TVBs increases their profit margin and hence the shout price and just as in the case of buyer agent, if there is no transaction then TVBs decrease their profit margin.

The profit margins are adjusted according to the following adaption mechanism: At a given time t, an individual ZIP trader calculates the shout price $p(t)$ with limit price L and using the profit margin μ(t) according to the following equation:

$$p(t) = L(1 + \mu(t))$$

According to ZIP strategy the value of μ for each trader must change dynamically (either increase or decrease) in order to make the trader's shout-price competitive when compared to shout price of other traders. This variation in profit margin is achieved through a machine learning rule - Widrow-Hoff "delta rule". Based on this rule, an update for the profit margin μ on the transition from time t to t+1 is done according to following equations:

$$\mu\,(t + 1) = \frac{(p(t) + T(t))}{L} - 1$$

Where:

$$T(t + 1) = \gamma . T(t) + (1 - \gamma). \Delta(t)$$

$$\Delta(t) = \beta. (\tau(t) - p(t))$$

$$\tau(t) = R(t). q(t) + A(t)$$

Here in these equations $\tau(t)$ is the target price, β is the learning rate and γ is the momentum coefficient. $R(t)$ and $A(t)$ are the random real and $q(t)$ is the last shout value. When it is required to increase the agent's shout price then $R(t)$ > 1.0 and $A(t)$ > 0.0; however when it is required to decrease the shout price then 0.0 < $R(t)$ < 1.0 and $A(t)$ <0.0.

The values for all the above described variables have been adopted from the prior work done on ST markets in Caicedo (2009). Thus accordingly R is uniformly distributed over the range [1.0, 1.05] for price increase and within the range [0.95, 1.0] for price decrease. A is uniformly distributed over [0.0, 5.0] for price increase and [-5.0, 0] for price decrease. β is fixed at 0.3 and γ has the value of 0.05. To start off the auctioning process initial profit marginsμ, are randomly generated to be within 5% and 35% for MOs and TVBs.

Appendix C: *Long-tail curves*

Here we present the figures obtained from the analysis of total volume of traffic carried through different operator (MO and LAO) network for remaining LAO configurations (30x30 and 90x10) which were not illustrated in the results chapter. As discussed before the figures have a long tail shape with MOs carrying the bulk amount of the traffic and forming the head, while the LAOs constituting towards the tail. Figure C-1 to Figure C-4 illustrates how the shape evolves under different LAO configurations i.e. 30x30 and 90x10. We also illustrate an expanded view of the tail part of the distribution for better clarity.

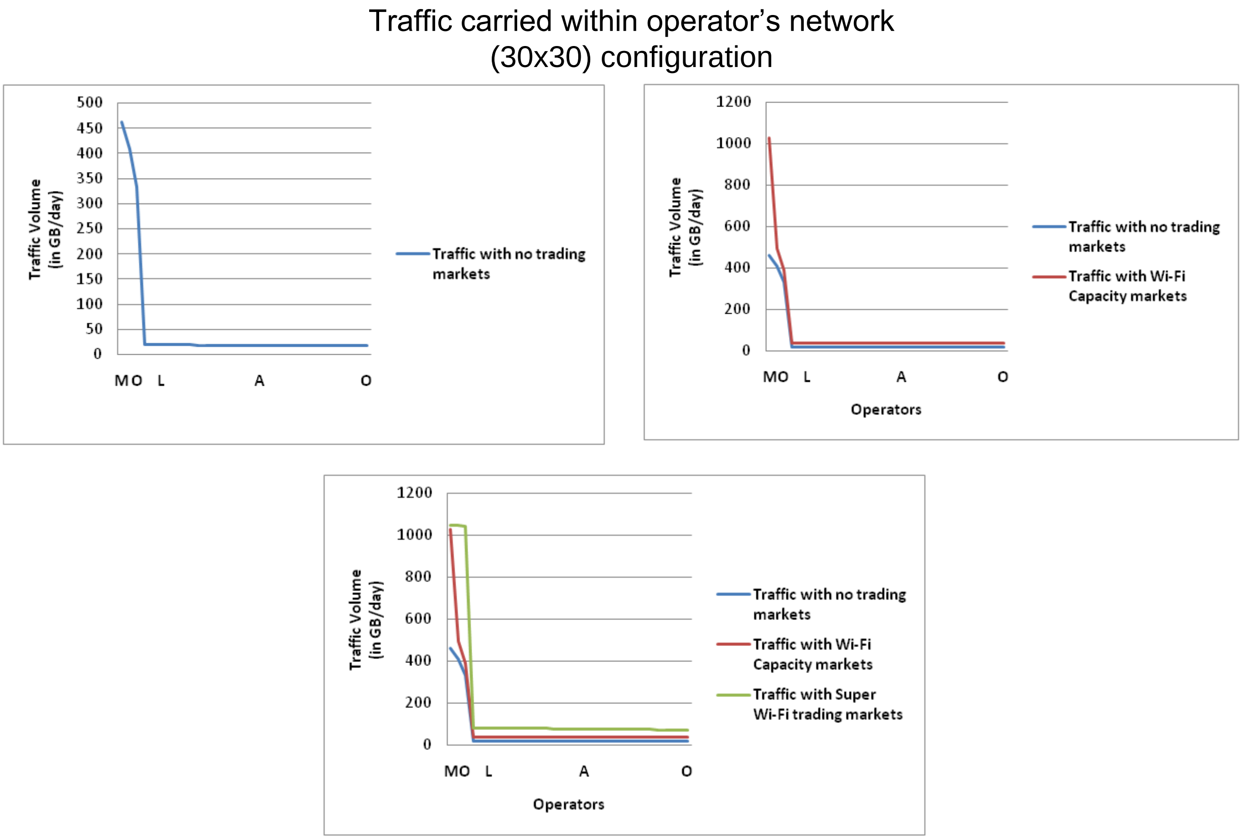

Figure C-1 Evolution of long tail shape of traffic volume from one trading case to other (30x30 LAO configuration)

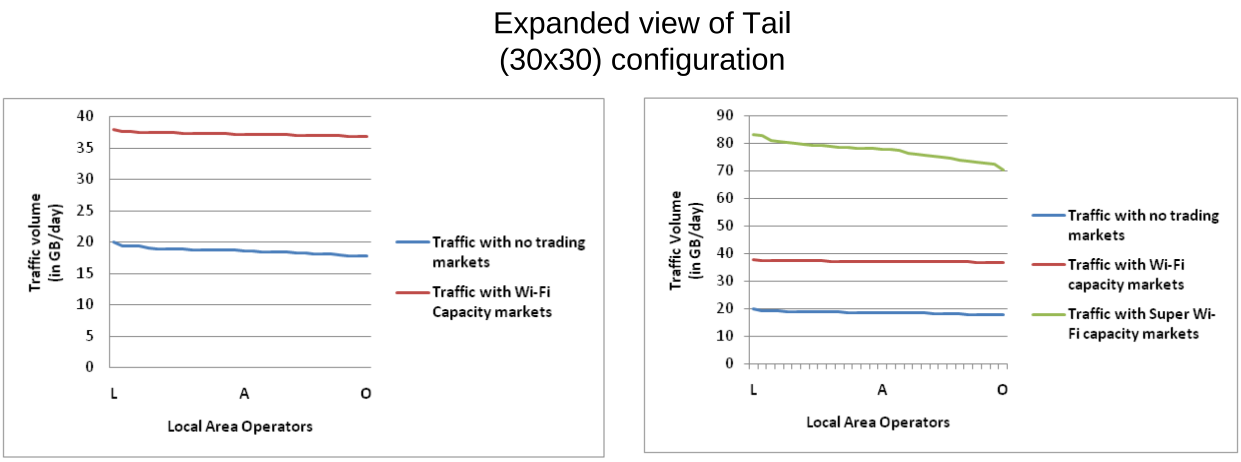

Figure C-2 Expanded view of tail for 30x30 LAO configuration

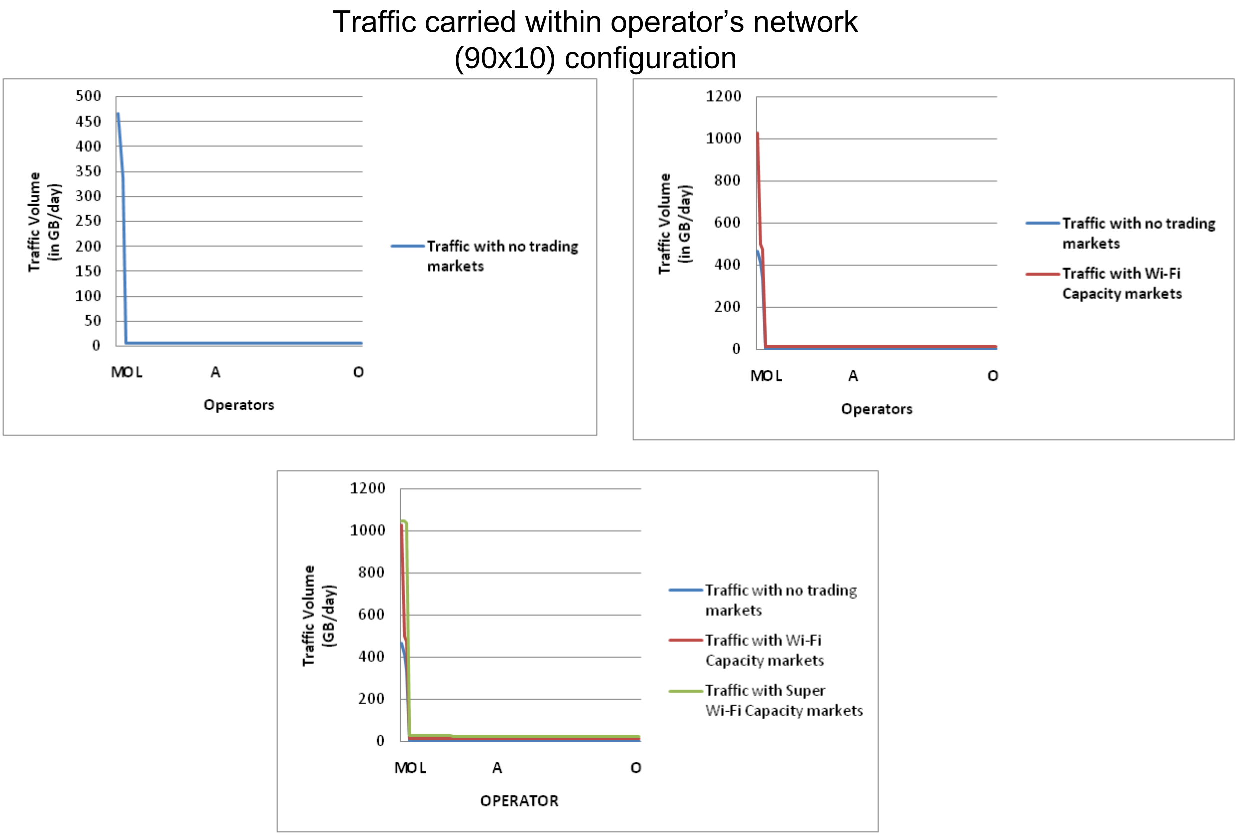

Figure C-3 Evolution of long tail shape of traffic volume from one trading case to other (90x10 LAO configuration)

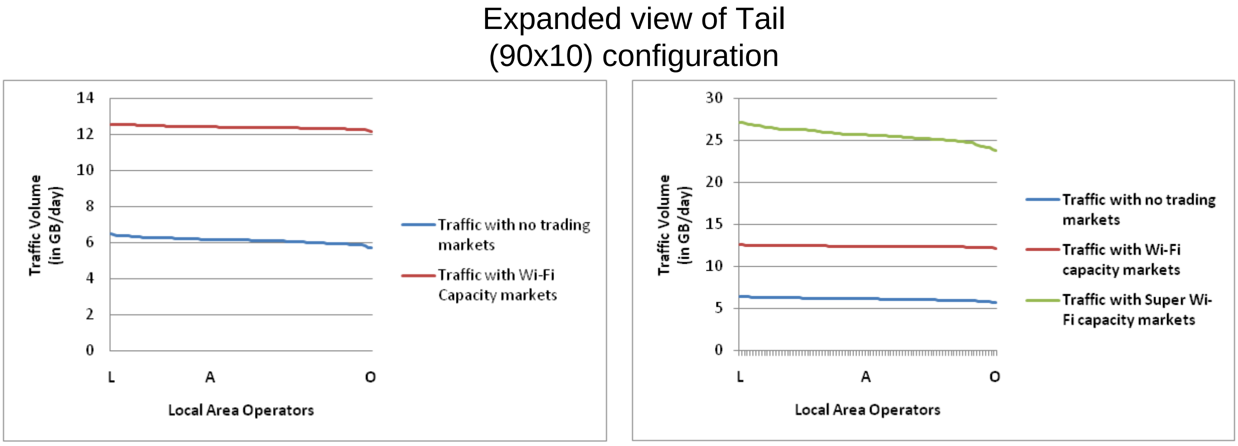

Figure C-4 Expanded view of tail for 90x10 LAO configuration